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Sustainable Design and Manufacturing 2016

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Preface

This volume forms the proceedings of the Third International Conference on Sustainable Design and Manufacturing (SDM-16), organized by KES International and Cardiff University, UK in collaboration with the Technical University of Crete, Greece between 4 and 6 April 2016.

This conference provided excellent opportunities for the presentation of interesting new research results and discussion about the theory and applications in the field of sustainable design and manufacturing, leading to knowledge exchange and the generation of new ideas. This field includes both the design and manufacturing of sustainable products and the sustainable design and manufacturing of all products. The application areas included all the activities during the product life cycle and other activities such as modelling and simulation, decision support, production planning and control, logistics and supply chain management.

The conference programme was very exciting with over 60 papers to be presented across 12 parallel sessions. We were privileged to have had three keynote speakers: Prof. Gül E. Kremer, Professor of Engineering Design and Industrial Engineering, The Pennsylvania State University; Dr. Andy Clifton, Sustainability Manager for Engineering & Design, Rolls-Royce, UK; and Dr. Bin Song, Senior Scientist, Singapore Institute of Manufacturing Technology (SIMTech), Singapore.

We would like to take this opportunity to acknowledge the effort and work put in by all those people who made it possible to organize SDM-16. We are grateful to the scientific committee, to the supporting organizations and the members of the organizing committee for their efforts to ensure that this conference is a success.

We hope that the conference proceedings form a useful and interesting foundation for further research into this evolving and vibrant field.

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Part I
General Track 1: Sustainable Design, Innovation and Services

A New CAD Integrated Application to Support Designers and Increase Design Sustainability

Giampaolo Campana, Mattia Mele and Barbara Cimatti

Abstract The design of any industrial product requires a development process that takes time and implies costs. In order to increase the sustainability of this activity it is necessary to study and generate new methods and techniques for its optimization, supporting the designer with tools able to quickly allow him to choose the best product solution. This activity includes the implementation of tools that, by interacting with a CAD, can add further automatic operations as, for example, the optimisation of the model basing on the environment or, more generally, on the integration of some sustainable aspects by an automated process including an evaluation of the proposed product. The software SFIDA, Sailplane Fuselage Integrated Design Application, is a first attempt to implement a tool that complements CAD, collecting some of the key aspects of the design of a specific component, managing their relations and optimizing their combination; in particular, the chosen case study is the fuselage for a single-seat glider. The use of this application allows designers to save time as it offers the possibility to quickly operate on a wide set of parameters that define the target product, leading to different models among which the best one can be chosen. A further advantage is the opportunity to modify the design of the object at each step of the process without affecting the consistency of the entire model and quickly visualizing several possible solutions. The concept of SFIDA can be applied to different products and domains giving the possibility of further development and improvement. This tool can therefore be considered a significant upgrade of any CAD system used to design industrial products.

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In particular, this approach is suitable when the object dimension and shape can be affected by limits and constraints deriving from different features and targets, such as the spatial collocation of the component and the interaction with other elements.

Keywords Design · Sustainability · CAD · Product development · Time

1 Introduction

Sustainability is a topical issue nowadays and a sustainable approach is sought in any field, even if it first appeared in biological and natural sciences at the end of the 19th century, in particular referred to forests [1]. The World Commission on Environment and Development (WCED) first defined in a famous report entitled "Our Common Future" in 1987 sustainable development as what meets the needs of the present without compromising the ability of future generations to meet their own needs [2].

One of the most important domains where the attention has been concentrated is industrial production. Any object should respect some sustainable criteria in terms of respect of the environment, a good balance between performance and cost, and social attention and care. Then the three dimensions of the Triple Bottom Line: Environment, Economy, Society [3] should all be considered to make industry sustainable.

The first steps in order to manufacture any goods are ideation and design. It follows that Sustainable Design has become a popular and studied theme in order to provide new solutions to designers who need methods and tools to design products, taking into consideration the above mentioned aspects.

The environmental issue has been the first aspect faced and deepened in sustainable design. Many terms such as eco design, ecological design, green design, environmental design have been coined to describe a design approach focusing a choice of materials and of production processes respecting the planet, preserving the natural resources and limiting pollution, along with avoiding the creation of wastes difficult to dispose of, once the product has finished its cycle of life. But the environmental dimension is not the only one of sustainability and economic and social aspects have increased their relevance within a sustainable design approach.

Designers must contribute to increase the number of alternatives, which means strategies of solution to the problems, technically and economically practicable by consumers/users [4]. To be able to correctly choose the best solution in a short time, designer must be provided with adequate tools. Then new methods and techniques allowing a quick identification of the most feasible and convenient variation of the product are sought. The improvement of the design method and the reduction of the time needed to develop the product correspond to an increase in sustainability.

A number of research papers dealt with the discussed topic and in [5], for example, a novel methodology for enabling Multidisciplinary Design Optimization (MDO) of complex engineering products is proposed. The concept of High

Level CAD templates was proposed and discussed. Besides, a quantification of the terms flexibility and robustness were presented with the aim to provide a measurement system of the quality of the geometry models. The applications have been applied for automating the design of transport aircrafts, industrial robots and micro air vehicles.

An innovative methodology for optimising designs was proposed in [6]: the authors combined a design generation tool with an analysis software and an evolutionary algorithm. The evolutionary algorithm was used to generate a range of aircraft by two optimising rules and a constraint: maximise lift, reduce drag and remaining within the framework of the original design. The proposed approach allows the designer to automatically optimise the design procedure.

In [7] a method which enables an automatic product form search or product image evaluation by means of a fuzzy neural network and genetic algorithms was proposed. A feature-based hierarchical computer-aided design (CAD) model was constructed in order to facilitate the automatic generation of new product forms.

The aim of the research work here presented can be considered a first step of a more complex tool that will be developed to include new functions to a Computer Aided Design (CAD) system with the aim to add new automatic tasks. The idea was implemented in a simple case study with the aim to improve the design of the fuselage for a single-seat glider, including automatic tool for satisfying the pilot's need to comfortably drive the aircraft. The method can be theoretically applied to different kind of industrial products, then this tool can have a wider use.

2 Description and Operation of the Software SFIDA

SFIDA (Sailplane Fuselage Integrated Design Application) is a tool for CAD developed at the University of Bologna. This application is here briefly described in order to provide a basic example of the design approach introduced in the first section. The aim of SFIDA is to collect some of the key aspects involved in the design of a specific component (which is the fuselage for a single-seat glider) managing their relations. This application has been developed as an independent software which is able to dialogue with PTC Creo© to build solid CAD models. A simple opening window (Fig. 1) allows navigating the different functions of the program; the disposition of menus suggests a sequence of operation in order to manage product's parameters, nevertheless it is possible to manage them in a different order to perform the decision-making process with the highest freedom. More windows can be opened and managed at the same time in order to obtain a more complete overview on the different issues.

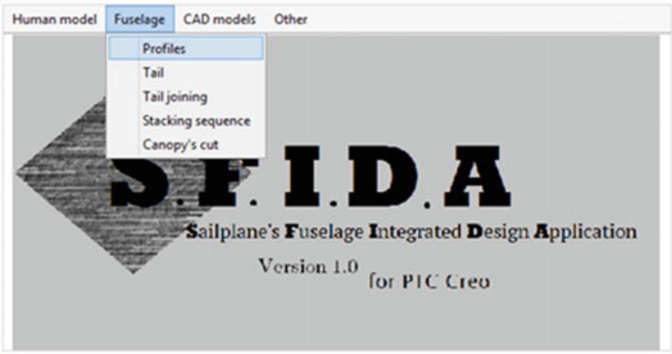

Fig. 1 SFIDA opening window

2.1 Design Constraints

The first step of the logical process investigates the constraints the design of such a component is subjected to or, at least, the ones the application should consider.

First of the person has to seat inside the cockpit in order to pilot the aircraft. This very simple statement is translated in a wide list of requirements concerning both fuselage and the pilot's body itself (or, more accurately, the model of it). As an example, the dimensions of the cockpit must allow the pilot's necessary movements to steer the aircraft and not all the positions are suitable to drive the aircraft.

Therefore, the first menu is dedicated to the generation and ergonomic analysis of a model of the pilot that is used in the following steps to investigate its interaction with the system. The window used to define pilot's posture, shown in Fig. 2, is an example of how constraints are included in the application.

The pilot's posture is defined handling the relative angles of different articulations using sliders or typing in angular values; each of these parameters can be

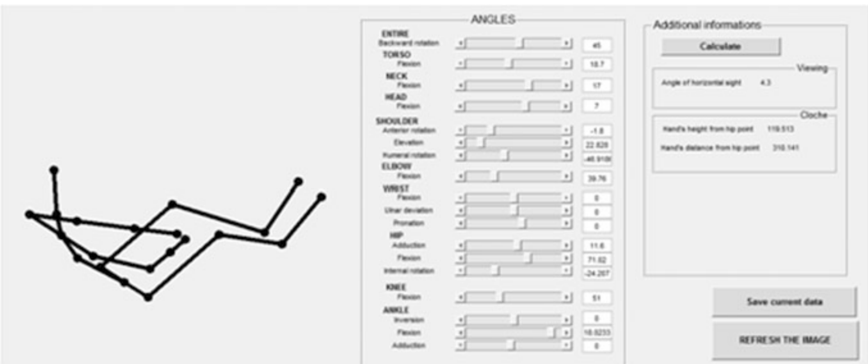

Fig. 2 Pilot's posture definition

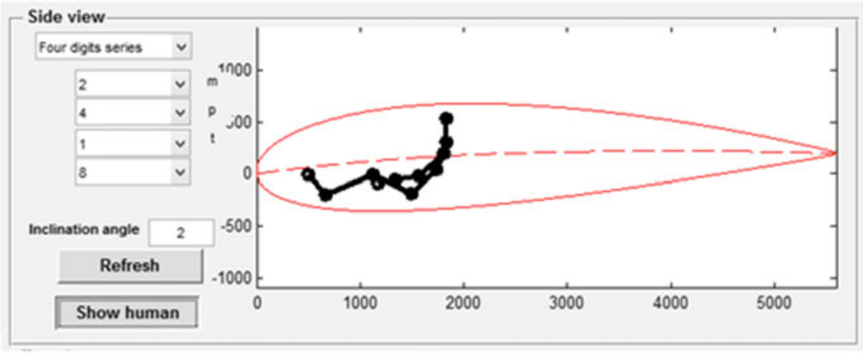

Fig. 3 Definition of side view air foil digits

modified within a range deriving from the intersection of generic anatomical constraints and specific requirements. As an example, the number of angles is reduced according to the condition of symmetric posture, as well as the backward rotation of the model can move from 0° (standing position) to 75° (extremely reclined position).

The fuselage profile is subjected to many constraints: first of all, the rear part of the airframe is designed basing on two air foils according to 4 or 5 digit series for the top and side view as proposed by the National Advisory Committee for Aeronautics (NACA), as shown in Fig. 3.

The definition of digits and side angles completely defines the shape of the two curves (for a chord value set by user). In Fig. 3 it is possible to see how the pilot model (with anthropometric values and posture previously defined) is displayed in a perspective view to immediately check interferences; the user can also check the relative position of the pilot and the air foil. Once the transversal sections have been defined, a check tool is available to measure the distance between the fuselage and the pilot's body.

This kind of approach allows to quickly and easily sketch the curves needed for the interpolation, considering the presence of pilot.

2.2 Design Variables

The definition of the articulation angles for the pilot posture and the digit assignment for NACA air foils, shown in the previous paragraph, are examples of design parameters the user can set within a constrained range affecting the global design result. Another example, allowing more degrees of freedom, is provided by the window (shown in Fig. 4) used to set the anthropometric measures for the human model of the pilot.

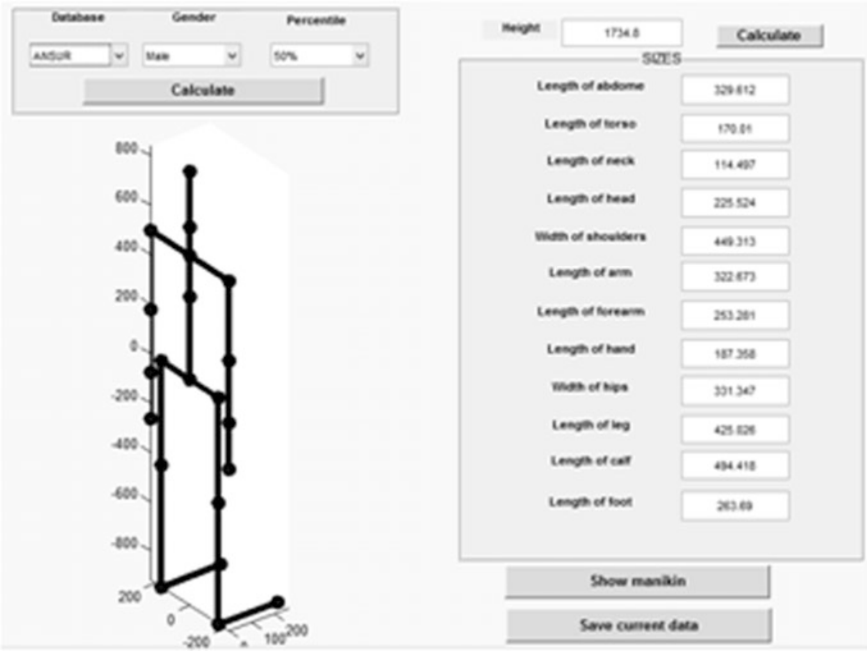

Fig. 4 Anthropometric settings

The multiple parameters can be assigned in three different ways. The first uses the anthropometric databases organized for geographic area, gender and percentile. The second approach is a relational model based on the height of the pilot fundamental to define all the dimensions. The third way implies the possibility of directly typing each size. Moving from the first to the third way the increasing level of detail allows sizing the cockpit for different applications.

It is relevant in this application the opportunity to manage parameters that are not directly related to the fuselage geometry, but that are used by the program in order to determine it. A similar example refers to the definition of the visual field of the pilot, used for the generation of the canopy cut.

Geometric parameters are reduced to the minimum required number according to constraints coming from the application: as an example, Fig. 5 shows a panel used for the definition of a tail joining the air foil.

The only data required to the user are the ratio between the semi-axes of the inner ellipse used for joining and the tangency angle of the fillet. As the minor semi axis is determined by the maximum thickness of the air foil and by the relative positioning of the assigned tail, these two data are sufficient to completely describe the geometry of the airframe in the side view.

The design process is developed taking into account ergonomic considerations: a first example has been provided by the air foil definition (the curves are represented by the projection of the human model). Another example comes from the definition

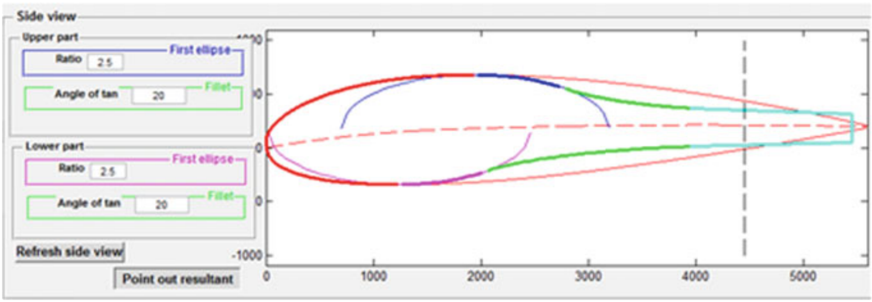

Fig. 5 Tail joining

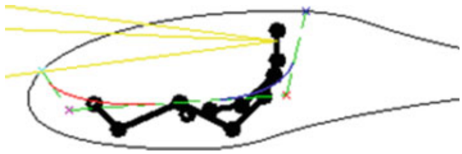

Fig. 6 Side definition of canopy cut

of the canopy: the visual field of the pilot model assigned by the user allows verifying the intersection with the transparent part of the cockpit (Fig. 6).

Both graphical representation and used parameters are chosen in order to optimize the combination between the visual space and the used material to resist in case of crash; therefore, elliptical fillets are defined by the percentage of the segments where their extremities are located (unlike, for example, the ones for the tail joining).

2.3 *Check Instruments*

During the intermediate steps of the design process, many check instruments are introduced in order to analyse the consequences of the user choices. As an example, in the right part of Fig. 2, it is possible to see some parameters that are automatically calculated by the program in order to describe the effects of a change in the angles to define the posture. This allows to immediately understand the effects of any choice on the final result. A deeper analysis of the posture is provided by a specific function of comfort analysis, shown in Fig. 7.

The posture, displayed on the left, is compared with a comfort model selected into the dropdown menu and briefly described in the left panel; the application shows in green the angles according to the purposed ranges, while in red the other ones. This quick tool gives an immediate perception of the comfort and can be used iteratively, at the same time of the posture definition.

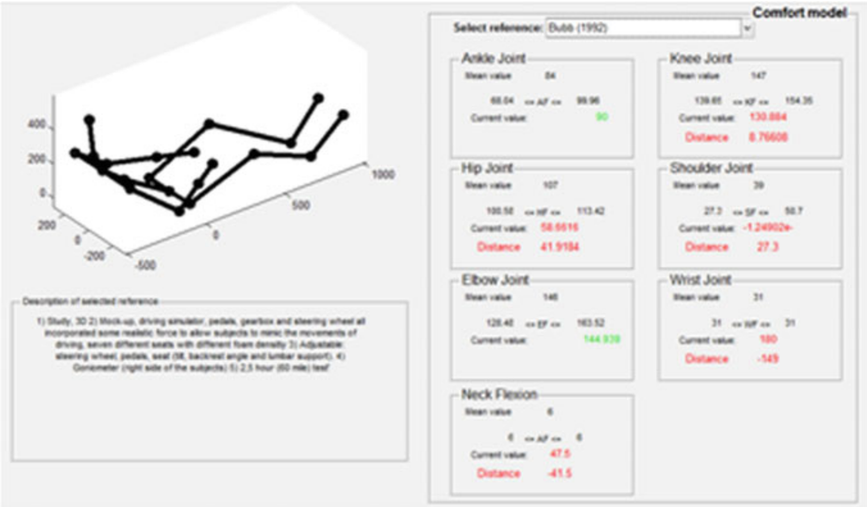

Fig. 7 Comfort analysis of posture

Fig. 8 Stacking sequence definition

Another example of the check function is the window used to assign the composite stacking sequence, shown in Fig. 8.

The stacking sequence is defined adding plies of different materials commonly used for the production of the component. When the laminate is defined, the check tool can be used in order to identify possible difficulties in the production and usage of the component, e.g. the absence of a safety Kevlar ply inside the carbon glass fibres to protect the pilot in case of crash or the formation of droplets on the external surface due to the interaction between PUR and the release agent.

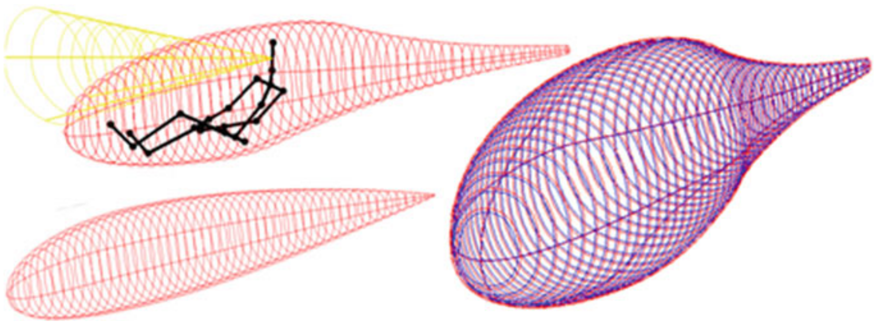

Fig. 9 Some 3-D previews provided into the application

Finally, a very important check tool used in many different steps of the application consists in three-dimensional basic representations of the system, which are useful to quickly verify intermediate results (Fig. 9).

2.4 Output

The output of the application consists in a design configuration derived from the decisions operated in each step of the process. Multiple CAD models of fuselage, canopy, manikin of pilot and of their assemblage can be generated and saved by SFIDA. In this study the output formats are generated for PTC Creo©. The CAD format also offers the opportunity to further modify the model in the following design phases to achieve a detailed design of the component.

The CAD model is structured to avoid possible errors during the regeneration process, because it can be generated independently by the configuration set: internal and external surfaces are both analytically calculated by SFIDA then used in the CAD software as boundaries of solid construction. This approach allows using any value of the fuselage thickness that can be automatically set, avoiding the common errors due to the use of different techniques, such as the offsetting of the surfaces or the shelling of the filled solid.

The application offers the possibility to operate on a wide set of parameters (directly or indirectly related to the geometry of the fuselage), leading to very different models as presented in Fig. 10.

For both internal and external surfaces four basic curves built with NURBS interpolating 120 knots each and 30 transversal sections (with conic-branches also defined by the user) are adopted.

This application allows managing a wide set of parameters (directly or indirectly related to the geometry of the fuselage) and leading to many models very different one from each other, as presented in Fig. 10.

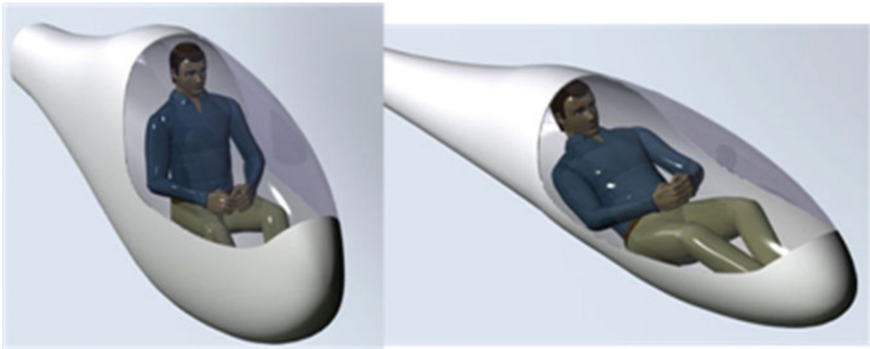

Fig. 10 Different outputs obtainable by the use of SFIDA

It is important to remark that such differences are due to decisions concerning the product instead of the geometrical model, each of them is justified and the entire design process is completely explained and modifiable within the application.

A traditional modelling approach of the system presented takes a long time. SFIDA allows reducing the time necessary to develop the CAD model, decreasing the whole time needed for the product development. A further advantage is the opportunity to modify each step of the process without affecting the consistency of the entire model.

3 Conclusions

A new tool to support designers during the definition of a fuselage for a single-seat glider has been proposed. SFIDA is a Sailplane Fuselage Integrated Design Application that complements CAD, collecting some of the key aspects of the design of the fuselage, managing its relations with the seat and the pilot driving the aircraft by optimizing the combination of the several parameters involved.

This application can increase the sustainability of the process of development of any industrial product, as it reduces the time that designers must dedicate to the CAD modelling and to the definition of the right composition of parameters, proposing several solutions and optimizing the interaction of the designed object with possible elements interacting with it. In the examined case the SFIDA is used to identify different models of fuselage, considering the reduced space of the cockpit where the person who has to drive the glider must fit. This tool can anyway have a wider use, being successfully applied also in other cases.

A further aspect of this application connected to sustainability is the anthropomorphic relevance. The design of the fuselage and of the seat can be connected to the territory, in terms of the physical characteristics of the local population representing the target market. For instance, the average height and weight of a possible pilot who will enter the cockpit to drive the glider can be considered to choose the best solution. Further research is needed to improve the application, in particular focusing this last point.

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A Conflict Analysis and Resolution Method Based on Integrating the Extension and TRIZ Methods

Zhao Yanwei, Lou Jiongjiong, Ren Shedong, He Lu and Gui Fangzhi

Abstract To address the issue that traditional and single design methods cannot resolve modern conflict problems quickly and effectively, which have become increasingly complex, we propose a new method for analysis and resolution of conflict based on integrating the extension and TRIZ methods. First, we summarize research on integrating the extension and TRIZ methods and then we analyze and build models for their transformation. In this way we can unite the strict reasoning ability of the extension method with the abundant practical experience of TRIZ to resolve conflict problems. To verify the correctness and feasibility of the proposed method, we apply it to the problem of reducing the noise of a screw compressor.

Keywords Extension · TRIZ · Design method of integration · Conflict analysis · Conflict resolution

1 Introduction

The extension method [1] and the TRIZ method [2] are two methods to resolve contradictions problems. The extension method offers qualitative and quantitative analysis but lacks practical experience; and the TRIZ method makes use of abundant practical experience and is supported by a numerous outstanding patents but lacks a model. Integrating the extension and TRIZ methods can solve some of their problems.

Qiu et al. [3] researched the similarities and differences between the extension and TRIZ methods and concluded that they are different in terms of contradiction

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classifications, theoretical basis, and researching objects and method systems, but they are similar with respect to the philosophical thought in solving problems. Zhou and Chen [4] researched the essence of the 40 invention principles of TRIZ and described them by extension transformations item by item. Li et al. [5] and Zhao et al. [6] compared the difference of their objectives, analyzed the difference of programs, and analyzed the differences in definitions and classification on conflict problems. They noted the need for further discovery on how to integrate these two methods. Zhao et al. [6] reviewed the application of extension and TRIZ methods and compared them based on their principles and applications and proposed integrating the two methods.

To extend this previous research, in this paper we propose a new method for analyzing and resolving confliction problems based on integrating the extension and TRIZ methods. First we express engineering parameters by using extension basic-element theory and integrate extension reasoning method and the TRIZ substance-field model and contradiction matrix, enabling us to develop a concept design program. As an application to verify the correctness and feasibility of the new method, we use it to design a lower noise screw compressor.

2 Transforming the Modeling of Extension and TRIZ Methods

The common central core of extension and TRIZ methods is to solve conflict problems, so their models can transform between each other, and it is the base of researching their integration.

2.1 Transforming Engineering Parameters of TRIZ to Extension Method

Transforming the engineering parameters of TRIZ [2] to extension basic-element theory is useful for not only expressing the engineering parameters in more detail but also expanding them to adapt to more questions. Engineering parameters can be classified into static engineering parameters and dynamic engineering parameters.

A static engineering parameter can be expressed by a matter element or multiple elements of the extension quantitatively. Taking engineering parameter 1 for example, the moving objects can be expressed by a matter element M = (Om, Cm, Vm) = (Om, speed, Vm), so all engineering parameter can be expressed by multiple element M1 = (M, C0, V0) = ((Om, speed, Vm), quality, V0).

A dynamic engineering parameter can be expressed qualitatively by an affair element, a relation element, or multiple elements. Taking the engineering parameter 14 (speed), for example, we can express this by the affair-element M1 = (Om, Cm, Vm) = (Om, speed, Vm), and gathering the affair-element and matter-element

A14 = (enlarge, control object, (Om, speed, Vm)) = (enlarge, control object, M1). After that, we can expand them by using the divergence method in the extension and get element sets for solving conflict problems.

2.2 Transforming TRIZ Inventive Principle to Extension Method

By combining it with extension method, TRIZ inventive principle [2] can be expressed quantitatively and its key information can be displayed, making it more comprehensible and formal and simplifying its implementation. The TRIZ inventive principle can be classified into an incompatible problem solving principle and an opposite problem solving principle based on the thought of invention principle solving problems.

For the incompatible problem, we express the conflict problem corresponding to the inventive principle, by using the extension model and then transform the model by the way of TRIZ method using the extension transformation method. For example, when someone falls onto a table, how to protect that person from becoming hurt? We can use the 14th inventive principle: surface. We can build extension model $P_{I14} = G_{I14} * L_{I14}$. G is the goal of the product, L is the condition. We can use transform tool T_{I14} replacement to change the right to rounded corners.

For the opposite problem, we can use the primitive theory of the extension method to express the target and the condition. And then we build a model of the extension problem. Finally, we transform the conditions by using the extension solution to obtain the final solution. For example, we desire a tank to have suitable armor while also having good maneuverability. We can use the 40th invention principle: composite materials to analyze. The final tank goal can be expressed as $G_{I40} = M_1 \wedge M_2$, where M_1 and M_2 are two ways to achieve the goal, increasing the thickness of the armor to increase damage resistance, and reducing the thickness to increase maneuverability. Based on this, the model of the extension problem is $P = G_{I40} * L_{I40}$. Then we do the extension transforming on the tank armor. $M//\{M_{01}, M_{02}, M_{03}\}$ = {Main armor, Inner fold, Backplane}, we replacing the inner fold material by composite materials.

2.3 Transforming Factors of Conflict of the Extension Method to TRIZ

Based on the number of characteristics that cannot meet the need, we can classify the conflict into two parts: single-factor conflict and multiple-facto conflict.

For a single-factor conflict problem, we can express the need characteristic by the tool of the extension to target G = (optimize, technical parameters, xin → xjm) and the objective conditions to L. Then we expand the structural parameters and get the detailed and base parameter characteristics of the problem.

Multiple-factors conflict problems can be classified into two types: those in which conflict parameters are independent and parameters are conflicting with each other. For the first type, we can use the single-factor conflict method to build the model. For the second type, we first need to build the parametric mater-element model of the design characteristic, then, by extension analysis of the parameters model, get the base characteristic parameters.

Finally, we match the parameters to the engineering parameters of the TRIZ to get the corresponding engineering parameters Ypi1 and Ypi2.

3 Analyzing and Resolving Conflicts Based on Integrating the Extension and TRIZ Methods

We have learned that conflict problems based on the extension and TRIZ methods can be classified into two types: single-factor conflict and multiple-factor conflict. Consequently, when we analyze and resolve the conflict problems, we can also classify them into two parts.

3.1 Analyzing and Resolving Single-Factor Conflict Problems

According to the definition of the extension, single-factor conflict problem belong to the incompatible problem. The analysis and resolution process is shown in Fig. 1.

According to TRIZ theory, one can use the substance-field model or separation principle to analyze the single-design-factor conflict problem. According to the engineer parameters, for the design requirement performance for two opposite states, when one requirement is met, the other will cease to be satisfied. We can use the separation principle to analyze and resolve the problem. It is the dependent contradiction problem in the extension, so we can use compatibility strategy to analyze it.

An affair element model of the extension based on the spatial separation principle can be built such that

$$A = (O_A, c, v) \| \{ (s_i)(O_A, Y_{PRir}, v_i); (s_j)(O_A, Y_{PRjr}, v_j) \} \quad (1)$$

where A = (OA, c, v) is an affair-element model, si and sj refer to different space conditions, respectively, vi is the value of YPKir in condition si. The other separation principles [2] offers a similar way to build the affair element model of the extension. Then the confliction problem can be solved by the appropriate inventive

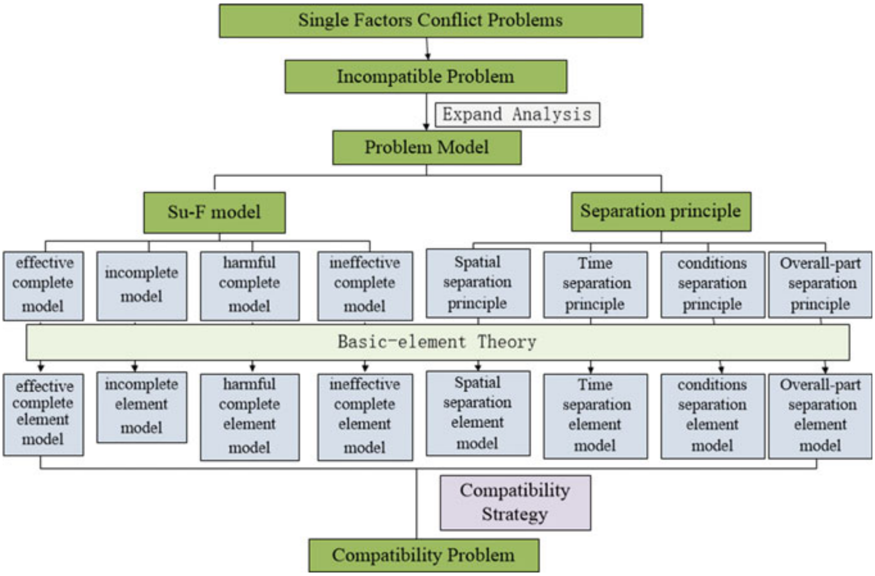

Fig. 1 Analyzing and resolving the single-factor conflict process based on integrating the extension and TRIZ methods

principle, which is strong to operate and give details of the conflict coordination strategy.

If the design demand can be expressed by a homogenous change, we can use the material field model [2] to resolve the conflicts. First, we build the extension model to describe the problem that can specify the function of a single design need:

$$\begin{aligned} P &= G_{PRi} \rightarrow L_{PCi} = M_1 * (M_2 v M_3) \\ &= (O_{M1}, c_{M1}, v_{M1}) * [(O_{M2}, c_{M2}, v_{M2}) v (O_{M3}, c_{M3}, v_{M3})] \end{aligned} \tag{2}$$

With the thought of extension method to resolve the conflict problem, we use extension transform and extension reasoning, combined with the standard solution Vi, i = 1, 2, 3, …76 which is corresponding to material field model to analyze and give the final solution.

3.2 Analyzing and Resolving Multiple-Factor Conflict Problems

The process to analyze and solve the multiple-factor conflict problem is shown in Fig. 2.

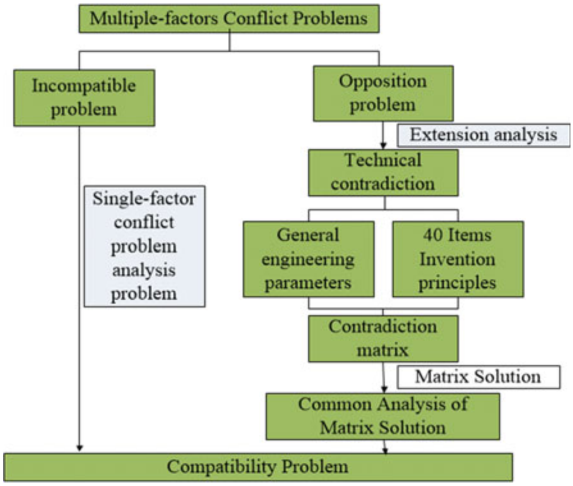

Fig. 2 Analyzing and resolving the multiple-factor conflict process

According to the previous discussion, we can see that we mainly need to solve the second type problem. First we need to extract the two opposite design parameters PRia and PRib from the design element of conflict and build the matching extension model

$$P = \left(GPR_i^a \wedge GPR_j^b\right) \uparrow L \quad (a < b, a, b = 1, 2, \ldots, l, 1 < l < n) \tag{3}$$

(where the symbol ↑ indicates that it cannot meet the need). Then we transform the contradictions in the process of real design to standard technical contradictions of the TRIZ and then match the GPRia and the GPRjb with the 48 general engineering parameter, obtaining the matching engineering parameters YPRia and YPRib. According to the technical contradiction matrix, which is built from the improved engineering parameters and the other parameters that may cause deterioration, we determine the corresponding matrix elements Mpri-prj, where the numbers i, j specify the number of the invention principle, and we identify the detailed invention principle according to those numbers. Finally, with reference to the method of coordinating the conflict problem of the extension, we build up a co-existence strategy based on the invention principle to resolve the multiple-factor conflict problem.

4 Example Verification

The main parameters of a screw air compressor are displacement, exhaust pressure, noise, volume, weight, rated power, and cost. First we retrieve information from the instance library [7] and get the incompatible problem. Second, we analyze and resolve the problem according the method of integrating the extension and the TRIZ methods. Finally, we construct a satisfactory plan.

We assume that the following performance requirements: *DP* (displacement) is medium, *EP* (exhaust pressure) is about 1.1 Mpa, the *NS* (noise) has no obvious impact upon nearby persons, *VM* (volume) is about 2300 dm^3 and the *RP* (rated power) is about 40 kW. According these performance requirements, we can transform them to the extension element model

$$PR_i = \begin{bmatrix} \text{screw air compressor} & EP & [0.9,1.3]\,\text{Mpa} \\ & DP & [5,7]\,\text{m}^3/\text{min} \\ & RP & [35,45]\ \text{kw} \\ & NS & [60,70]\,\text{dB} \\ & WH & [1000,1400]\,\text{kg} \\ & VM & [2000,3000]\,\text{dm}^3 \end{bmatrix} = \begin{bmatrix} PR_i^1 \\ PR_i^2 \\ PR_i^3 \\ PR_i^4 \\ PR_i^5 \\ PR_i^6 \end{bmatrix} \quad (4)$$

Because of the different dimensions for different data parameters, we need to normalize [8] the original data in the instance library. For some product characteristic parameters, such as the noise of the screw air compressor, it is customary to minimize their value. Thus we make the extension domain range [60,72] dB, with the optimum value being 60 dB. For other product characteristic parameters, such as the displacement, higher values are better. Thus the extension domain range for displacement is set to [4,8] m^3/min, with the optimum value being 8 m^3/min. By substituting the extension domain range and the optimal value into the multidimensional correlation functions and the similarity calculation formula, we can obtain the corresponding similarity value and the demand characteristic parameter number.

4.1 Analyzing Conflict Problem

According to the similarity value and the demand characteristic parameter number of the screw air compressor calculated, we can divide the instances that meet the condition Kn-9(PR) < 0 into a single-factor conflict problem and multiple-factor conflict problem. Such as 9#SAL37, which satisfies Kn-9(PR) < 0, Kn-8(PR) > 0, Knoise(PR) < 0. It is the single-factor conflict problem. Such as 13#SBL37, which satisfies Kn-9(PR) < 0, Kn-7(PR) > 0, Knoise(PR) < 0, Kdisplacement(PR) < 0, it is the multi-factors conflict problem.

4.2 Resolving the Conflict in the Large Screw Air Compressor Based on Integrating the Extension and TRIZ Methods

According to the analysis in Sects. 4.1 and 4.2, we obtain a single-factor conflict problem and a multiple-factors conflict problem. We choose the noise as the object of interest, with the help of PRO/INNOVATOR to analyze what causes the noise, and then give the solution.

Firstly we build the component model to the noise problem, as shown in Fig. 3. And the parts function model figure of the screw air compressor system will generate a set of "how to" transformation problem models to coordinate the problem of noise not meeting the requirement. The set of "how to" models is shown in Fig. 4.

According to the set of "how to" models, we can clearly discern which parts of the system cause the noise and then find the potential reasons through analysis of the original problem. In this section we will analyze the original problem of axial flow fan components (Fig. 5).

As an example problem model we consider the following: "How to decrease noise of axial flow fan?" The matching general engineering parameter is 31,

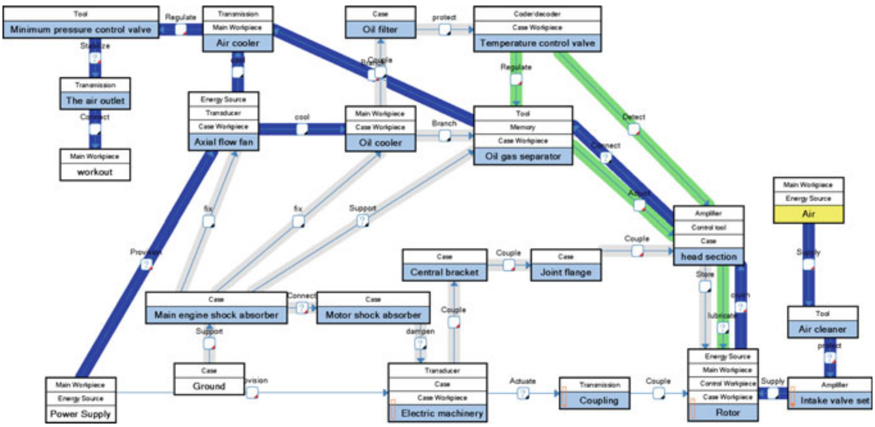

Fig. 3 Component model of the screw air compressor

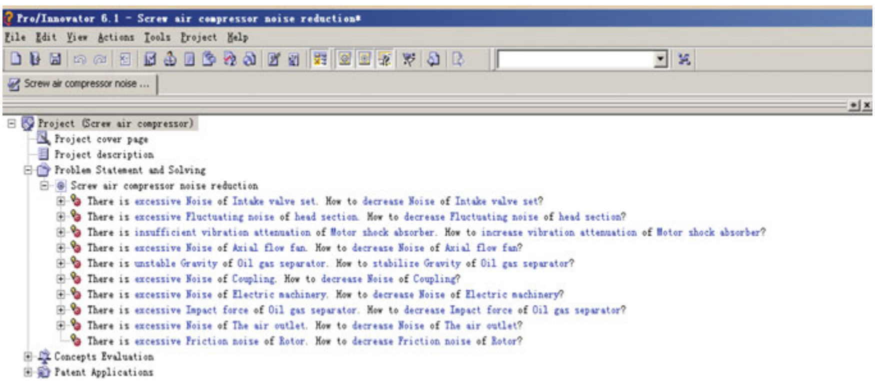

Fig. 4 Transformation problem models

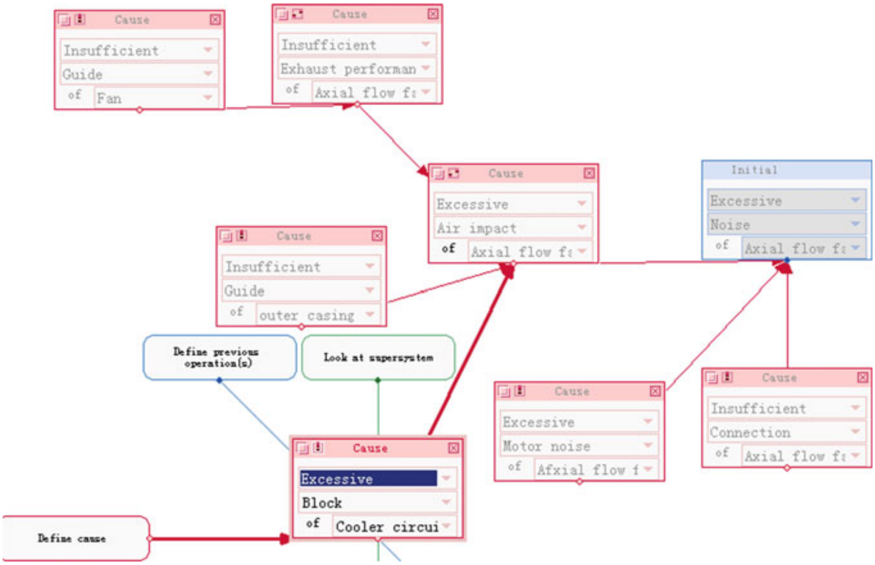

Fig. 5 Analysis of the noise of axial flow fan parts

object-generated harmful factors. Reducing the noise leads to an increase in the complexity of the equipment, so the general engineering parameter is 36, the device complexity. In PRO/INNOVATOR, the innovation principles given by contradiction matrix are 1, 19, and 31. According to PRO/INNOVATOR, we find the reference solution for the model of "there is excessive noise of axial flow fan. How to decrease noise of axial flow fan?," as shown in Fig. 6.

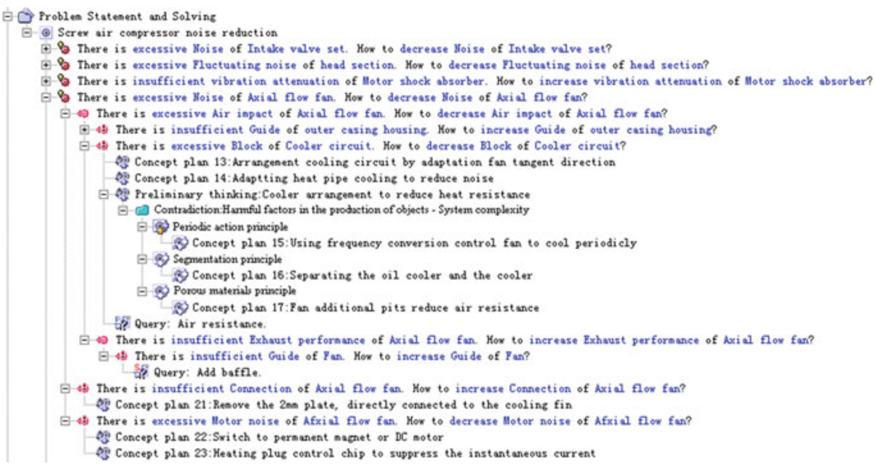

Fig. 6 Solutions for the noise of axial flow fan parts

#	preliminary idea	N,%	C,RMB	D,YEAR	Valuation		
1	Concept plan 3: Fan additional pits reduce air resistance	86. 00	800. 00	10. 00	100		
2	Concept plan 4: Improve the speed of the air in the fan by i mproved radial rib	88. 00	50. 00	12. 00	98		
3	Concept scheme 5: cooling pipe is designed to have the shape of the diversion capacity	84. 00	500. 00	12. 00	97		

Fig. 7 The first three results

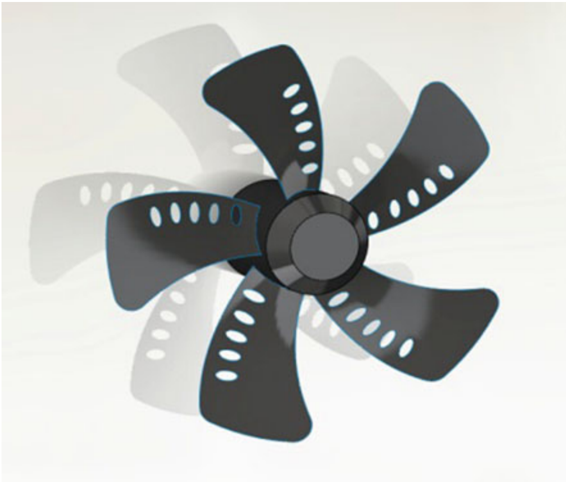

Fig. 8 Improved axial flow fan

Fourthly we choose three parameters (noise, cost, and use time) as the evaluation indices, and set the weights as 80, 15, and 5 %. Then we invited the experts to evaluate every solution. The first three results are shown in Fig. 7.

Fifthly we find that conceptual scheme 3, increasing the pits in the axial flow fan to reduce air resistance is the best solution. So we punch some holes in the blades of the axial flow fan which is shown in Fig. 8.

5 Conclusion

To address the limitations of current single innovation methods to solve the contradiction problem in complex product design, in this paper we researched the integration of the extension and TRIZ methods and built a model to resolve the conflict. Application of the model in a large screw air compressor verified that the method is correct and feasible. However, in this paper we only combined the general engineering parameters of TRIZ, the innovation principle, and the substance-field model with the extension element method; there are additional TRIZ tools that can be used.

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Investigating the Regulatory-Push of Eco-innovations in Brazilian Companies

Paulo Savaget and Flavia Carvalho

Abstract This paper presents eco-innovation as the means of harmonizing economic activities with environmental resilience. Several agents and factors are involved with generation and diffusion of eco-innovations; nevertheless, the role performed by the state, as an inducer of eco-innovation, is crucial. Little is known about the role played by governments in promoting eco-innovations. This work investigates the influence of regulations in generating eco-innovation in Brazil, through a statistical analysis originated by an unprecedented survey carried out with 98 Brazilian enterprises. Results suggest that regulations are keen on promoting organizational and process innovations, with incremental impacts and internalizing environmental externalities that are no longer tolerable by the government. A high number of regulatory-pushed eco-innovations were generated using economic mechanisms, such as funding and subsidies and came out of cooperative arrangements, mostly with suppliers. Regulations could also be influencing high-impact eco-innovations, opening up opportunities to suppliers of cleaner products and services.

Keywords Regulation · Government · Eco-innovation

1 Introduction

Industrial growth followed an accelerated pace since the industrial revolution, with new technological paradigms emerging and deeply changing societal behaviour, consumer preferences, industrial infrastructures, political frameworks and social wellbeing. However, contemporary patterns of manufacturing have led to techno-

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logical development patterns that are highly economically profitable but environmentally degrading.

On one hand, it seems obvious that innovation has played an important role to promote better livelihoods. It comes as no surprise that a large set of innovations since the industrial revolution improved, for instance, life expectancy of most of the world's population. Although improvements in social wellbeing have not been equally (neither fairly) distributed, it is unquestionable that society at large has benefited from industrial development. On the other hand, it is clearer than ever that planetary boundaries have been crossed beyond their natural resilience: or, in other words, beyond the ability of the environment to recover itself [1]. Natural systems are not exogenous to human activities. Instead, these systems are complex and co-evolving, directly affected by technological trajectories and social behaviour. If industrial patterns and social behaviour do not change, longevity and profitability of industries will face severe constrains and the ability of future human generations to meet their needs will be compromised [2].

The effect of industrial technology on nature thus raises questions about whether past trends of prosperity can be broadened—or even sustained—in the future [3]. Achieving greater harmony between economic development and environmental resilience requires a sea change in the current patterns of development. Changing the existing industrial paradigm requires alternative efforts from different agents to generate products, processes, services, technologies and business models capable of simultaneously benefitting the economy and the environment [4]. Eco-innovations are hereby presented as means of shifting society towards new paradigms: from business-as-usual to sociotechnical models that harmonize economic activities with environmental resilience.

There are various sources of stimuli to the generation and diffusion of eco-innovations: and the role of governments has proven to be critical. Market mechanisms are not enough to push firms to internalize the responsibilities (and opportunities) arising from environmental hazards [5]. Despite its importance, little is known about the subject, especially in countries with an emerging economy, such as Brazil. This paper therefore aims at contributing to the understanding of the role governments can play in promoting eco-innovations—and, consequently, the role of national regulations in contributing to a more innovative, economically profitable and environmentally resilient country.

2 Eco-innovation and Industrial Development

Finding solutions to environmental threats requires new relationships between society and nature that will drive the economic actors towards more sustainable pathways. Environmental challenges tend, nonetheless, to be viewed exclusively as constraints to human activity—although they can present great opportunities for economic and social prosperity [6, 7]. Fostering a better relationship between industrial activities and natural resources can create win/win situations for both economic and environmental performance. According to Cohen [6], society should pursue these new technological paths by exploiting opportunities for innovation to enhance the environmental performance of industrial processes. Evans [7] went further, presenting that companies are increasingly striving to deliver value when product development is constantly under pressure across their entire value chain; and, in this scenario, considerations beyond economic return should be considered both to mitigate risks and to create opportunities to innovate.

Despite great discussion in the academia, the observation that firms can drive innovation and build a growth trajectory through the internalization of environmental concerns still comes as a surprise when dealing with industrial managers and policy-makers [7]. Several studies have arisen in the past two decades to investigate what is nowadays framed as eco-innovation—including their types, determinants, and impacts over natural resources and the economy. It can be described as the production, assimilation or exploitation of a "product, production process, service or management or manner of doing business" [8], that results both in environmental gains—e.g. clean water, biodiversity resilience, and less carbon emission—and economic benefits for firms and nations—e.g. profitability, national competitiveness, and firms' longevity. It is important to stress that eco-innovations do not necessarily involve new knowledge or new technologies for the entire world: it might be restricted to the adaptation, absorption or imitation of technologies created elsewhere [9]. Innovations can be radical or incremental; the former includes discoveries that completely disrupt current activities, and the latter covers significant improvements to already existing products or processes.

Types of eco-innovations fit into different categories. The first comprises environmental technologies. These technologies may be remedial (end-of-pipe), reducing the effects of existing technology. They also can be clean alternatives to more-polluting technologies. The second category covers organizational innovations that incorporate environmental issues, including strategies applied to production processes, infrastructure and logistics that limit environmental damage. Internal audits, staff training, and waste and pollution prevention methods fall into this category [10].

Environmentally beneficial products and services, such as green certifications or biodegradable products, fit into the third category. Services include waste and pollution management, environmental consultation, and other activities that decrease the negative environmental impact of production methods. The fourth, and final category contains green innovations of systems, which "involve a wide range of changes in technological production, knowledge, organization, institutions and infrastructures and possibly changes in the behaviour of consumers" [10]. This category covers alternative systems of production and consumption that are more environmentally beneficial than existing systems, reaching a wide range of actors and broad sectors of economic activity.

It is also interesting to observe that the definition of eco-innovation prioritizes the environmental result over the motivation of the firm to innovate [11]. The literature does not discriminate between intentional and unintentional results. Discovering the determinants of eco-innovations is nonetheless essential, if eco-innovations are to be fostered systematically. Ekins [12] argues that there are several interrelated determinants shaping the emergence and diffusion of eco-innovations, which are: market pressures, managerial capabilities, ethical concerns and policy-push.

Although these categories are dynamically interrelated, this paper focuses on policy-push. The rather counterintuitive hypothesis proposed (and confirmed) by Porter and Van Der Linde [13] that environmental regulations foster efficiency and innovation is still doubted by sceptical academics, industrial managers and policy-makers. Regulations are not impediments to economic activities, as commonly presented in political discourses, but rather opportunities to increase competitiveness. More recent works have corroborated the importance of environmental regulations to eco-innovations in German [14] and English companies [15]. This paper will focus on the characteristics of policy-push (and, more specifically, the regulatory-push) over the generation and diffusion of eco-innovations in Brazilian firms and the next section will describe this relationship with further details.

3 Eco-innovation and Public Governance

Recommendations arising after the Brundtland Report [2] have signalized that, instead of merely mitigating environmental risks, policies should conceive environmental protection in a broader, proactive manner, by designing systemic environmental strategies and integrating them with industrial policies [16, 17]. Governance can seize many strategies, such as public procurement for nascent technologies, public funds to R&D, or subsidies to fair trade. The pursuit of these strategies involves a variety of incentives and is directly influenced by the prevailing institutional landscape and regulatory frameworks [11]. However, more than 20 years have passed since its publication, and examples of systematic policy stimuli to the generation and diffusion of eco-innovations are still rare. Furthermore, Pallemaerts et al. [18] described that EU members usually question the legitimacy of environmental policies and regulations through an undifferentiated discourse favouring short-term incentives to economic growth and employment.

Public governance incentives to eco-innovations fall into 4 broad categories of policy instruments, according to Jordan et al. [19]: (a) Market (economic)—with the goal of creating incentives to generate and diffuse eco-innovations; (b) Regulatory—focused on defining legal patterns to industrial and consumer behaviour; (c) Volunteer—in which agreements arise from negotiations between governments and/or organizations; (d) Informative/Educational—to better educate or inform enterprises and consumers. While comparing the effects of different kinds of policy instruments pushing eco-innovation, Oosterhuis and Ten Brink [20] argued that economic mechanisms—such as trade incentives and public procurement—tend to be superior to command-and-control. This is not a generalizable statement—a counter example is Germany, where regulations, instead of economic instruments, were responsible for the generation of more effective energy emission patterns [12].

Governments should increasingly combine these four tools, as means of improving the efficacy of their policies, besides controlling risks, reducing uncertainties and better dealing with the complexities intrinsic to technical progress.

Monitoring performance indicators is a complex task, not only due to the variety of possible stimuli to eco-innovations, but also due to the diversity of prevailing regulations, legislations and jurisdictions coexisting in a country. These policies and regulations need to be adapted to local contexts, and replicating policy frameworks from others will likely fail. They also involve decisions when "facts are uncertain, values in dispute, stakes high and decisions urgent" [21] such as deciding whether to focus on certain technological trajectories, or diversifying investments to a myriad of technological options. However, it seems clear, independently of the region to be analysed, that: (a) the priorities and needs are continually evolving and, consequently, instruments need to be constantly revised and adapted; (b) cooperation and coordination between research centres and industrial activities is particularly critical and (c) when markets are uncertain, national and international cooperation minimize risks and create synergies [11].

Although studies carried in high-income economies have tried to clarify the influence of public governance over the generation and diffusion of eco-innovations, little is known about the role played by governments in emerging economies, neither about the main characteristics of these resulting eco-innovations. This paper tries to contribute to fill this gap, by presenting the results of an unprecedented survey carried with Brazilian firms.

4 Methodology

This paper aims at answering the following questions:

- Are the Brazilian regulations fostering eco-innovations?
- If so, what are the main characteristics of eco-innovations and eco-innovators that were fostered by regulations?

The methodology applied in the research is quantitative; using descriptive and explanatory methods to approach data. In order to investigate the role played by regulations as a determinant of eco-innovations in Brazil, our descriptive and exploratory approach [22] consists of presenting and contrasting statistical indicators obtained through an unprecedented survey carried with Brazilian firms in manufacturing and services sectors.

The study employed a stratified random sample with companies of different sizes. Questionnaires were submitted electronically, using Survey Monkey® to design the questionnaire and explore responses. We got 98 responses to the survey, with a response rate of approximately 10 %. The sample was within the 95 % reliability interval with a significance of 10 %, which was expected for populations between 50 and 100,000, the approximate number of companies operating in Brazil [23].

The questionnaire has five sections: (A) general company data; (B) general information on the innovative activities of the company; (C) objectives of eco-innovations; (D) processes of eco-innovations; and (E) results of eco-innovations. Section A contained questions on capital ownership, revenues and share of revenues obtained from exports. Firms also were asked about the importance of environmental issues for their business as well as about the existence of environmental management initiatives (ISO 14001, sustainability report, among others). Section B included questions on companies' innovation activities, such as the amount of resources invested in innovation, expenditures on R&D and the sources of funds intended for innovation. Section C examined the nature and occurrence of eco-innovations more specifically. Section D focused on the processes involved in innovation activities, particularly, the sources of external knowledge used and whether cooperative arrangements for innovation had taken place. Finally, section E inquired about the results of eco-innovations and about possible barriers that would prevent eco-innovations from being successfully implemented. For the purpose of this paper we selected the most critical variables in this questionnaire to understand the relationship between regulations and eco-innovative activities—whose results are going to be presented in the following sections.

5 Results and Discussion

We received 98 valid questionnaires from firms. Most of the sample (58 %) was composed of large firms with more than 500 employees. Domestic firms comprised the majority of the sample (61 %); 22.4 % of the companies were owned by foreign capital, and 16.6 % of them had mixed capital ownership. The size of the firms in the sample also was evident in their revenues: 73.5 % of the firms had revenues higher than R$20 million (approximately US$10 million with the exchange rate of the period the survey was applied, in 2012). Most firms fall into the following sectors: Services (25 %); Machinery, Equipment and Technology (14 %); Mining and Steel (13 %); and Petroleum, Gas and Energy (10 %).

Of the 98 firms, 72 % reported the implementation of general innovations (of different natures, not necessarily eco-innovations): a high percentage compared to the innovation rate of firms in the Brazilian Innovation Survey carried out by the Brazilian Institute for Geography and Statistics (38.6 %). A simple explanation for the higher number was that firms interested in innovation and, more specifically, eco-innovations were more likely to voluntarily answer our survey—whereas the Brazilian Innovation Survey is mandatory and covers a much larger sample of Brazilian firms, including small and medium firms that our research team could not reach. While compared with the innovation rate obtained by the National Research for firms with more than 500 employees, however, the rate was similar. Therefore, even though our research was not representative of the universe of Brazilian firms (concerning sizes and economic sectors), there is a good level of accuracy in what regards, exclusively, innovation (and eco-innovation) by large firms (those with over 500 employees).

In general, most firms from our sample were aware of environmental issues affecting their businesses and were addressing these issues through a series of initiatives, such as waste management programs, energy consumption reduction plans, energy management systems and the creation of a sustainability team within their firms. Even though around 70 % of firms report being involved in environmental initiatives that can be considered either organizational or process innovation, only 46 % state undertaking eco-innovations. The reason is because, probably, some firms that present initiatives to address environmental issues do not consider implementation of managerial systems as innovations.

Regarding the determinants of eco-innovations, some interesting results have come out. New-business creation was, by far, the main determinant, as 23 % of respondents indicated this as the key driver to eco-innovation. This group of firms caught most of the attention, for the technologies or products they disseminate throughout the economy could enable other firms to employ more environmentally friendly production methods. In other words, eco-innovations are at the core business of these firms, so they approach environmental concerns strategically.

Cost reduction was the second most important determinant; 17 % of the sample firms stated it was the reason for their eco-innovation. We actually expected cost reduction to be the first determinant, a trend that would have conformed with the incremental approach to innovation more frequently employed by Brazilian firms. Cost reduction was followed by brand reputation and image improvement for 16 % of the respondents. These qualities were critical to businesses, especially large firms in industries that degrade the environment.

Complying with or anticipating regulations appears as the main determinant to the generation of eco-innovations for only 14 % of all eco-innovators. At a first glance, this result indicated that Brazilian regulations are either: (a) difficult to translate into innovation opportunities; (b) businesses do not anticipate future environmental regulations; (c) and/or that Brazilian environmental laws are not stringent enough to put firms on an eco-innovative path. Possibly, firms in our sample were eco-innovating beyond compliance, using environmental opportunities as a way to differentiate their companies in the marketplace. However, we dedicated a deeper analysis to investigate the types of firms mostly influenced by regulations to understand how this causal relationship occurs.

It is possible to observe that the majority of regulation-driven eco-innovations are organizational, followed by process innovations (35 and 26 %, respectively). Surprisingly, 48 % of these enterprises mentioned R&D activities destined specifically for eco-innovations. This result is rather surprising, as organizational and process innovations tend to be less scientific and high technological than other types, such as product and technological innovations. One possible explanation may be that eco-oriented R&D is still in process, and no outcome is already brought out.

Eco-innovations occur mostly through cooperative arrangements (65 %). The main partners for cooperation are suppliers (39 %). That derives from the need of firms to follow new regulatory demands through the purchase of services or new equipment. Consulting companies and other enterprises of the group come with 16 % each. Finally, 10 % of these firms had partnerships with universities as well as with clients and consumers. Not a single firm in this sample cooperated with NGOs.

It is also interesting to observe the outcomes deriving from eco-innovations fostered by regulations. The most frequent outcome was the reduction of environmental impact (65 %), followed by improvements in image/reputation (18 %); reduction of costs (12 %); generation of revenue and value (4 %); and improvement in the quality of products and services (4 %). It is also worth mentioning that no firm reported market share increase, neither the creation of new markets.

These results demonstrate that Brazilian environmental regulations are stimulating exactly what it commonly aims to: steering enterprises to lower their environmental impacts by adapting their productive activities. Command-and-control initiatives, such as regulations, are seen by our respondents mostly as enforcements to internalize externalities, reducing environmental hazards of their production. Also, there are few evidences of regulations guiding firms through products and services improvement—as it was mentioned only by 4 % of our respondents.

The profile of eco-innovative firms that have regulations as their main determinant is hereby critical to understand these results. They are normally large firms, which are mainly adapting their production to internalize externalities that are no longer acceptable by the government. However, when these large firms need to adapt, they normally have to purchase technologies from elsewhere: creating opportunities for other firms that are exploring new market niches that offer solutions to comply with regulatory demands (suppliers are the most critical source of cooperation for regulatory-pushed eco-innovations). The effect here is indirect but still very relevant to observe the impacts of regulations in fostering eco-innovations.

Indeed, regulatory-push is only ranked as the fourth most relevant determinant: the most relevant determinant, directly boosting eco-innovations, was creating new businesses. Nevertheless, these eco-innovators that are generating new businesses are also influenced by regulations, as they might be supplying demands for large firms that need to adapt to new regulatory enforcements. While most firms are focusing on reducing their environmental impacts with process and organizational innovation, some firms are developing new business models to supply services and products that are going to be needed in a larger extent, as regulations open up a variety of new demands (e.g. reverse logistics and cleaner technologies for production).

Therefore, it is recognizable that regulations have direct impacts on the reduction of environmental impacts but, also, have proven to be important for indirectly promoting the generation of new businesses by strategic eco-innovators—although the exact importance cannot be quantified in this study. We can conclude that in this sample the regulatory-push was not directly responsible for high-impact innovations, being mostly responsible for incremental innovations for compliance. However, as an indirect effect, regulations are also influencing the creation of new markets for new (and cleaner) products and services.

Also, when analysing regulation-driven eco-innovations, it is possible to notice that a great part of them used economic mechanisms such as subsidies and subventions—in other words, besides command-and-control, they were also influenced by economic mechanisms. Among them, 43 % are using subsidies for innovation, whereas 26 % are using, at different extents, public funding for their innovations. Economic mechanisms to promote eco-innovations are nevertheless rather restricted in Brazil, especially when compared to high-income countries (such as United States, Germany and South Korea) or China, that have demonstrated great sums of investments directed towards clean technologies, energy efficiency, biotechnology, renewable energy and hybrid automobiles [24].

6 Final Remarks

This study aimed at investigating how regulations induce eco-innovations in Brazilian firms through an unprecedented survey, carried by the authors in 2012 with 98 enterprises. Regulations were the key determinant for eco-innovations only to 14 % of respondents. The profile of regulation-driven eco-innovations was also analysed in further details: (a) they are mainly incremental improvements in process and organizational management; (b) aimed at internalizing environmental externalities that are no longer tolerable by the government; (c) were generated using economic mechanisms, such as funding and subsidies; and (d) came out of cooperative arrangements—mostly with suppliers (and these suppliers, in turn, can be generating more radical eco-innovations). It may be possible to infer that the regulation could also be indirectly influencing high-impact eco-innovations, as new regulatory demands open up opportunities to suppliers of cleaner products and services.

The analysis of the sample of Brazilian firms seems to reinforce the role of governments influencing the generation of eco-innovations, either through command-and-control enforcements, or through direct public stimuli (e.g. funding, public procurement, etc.) to an eco-innovative ecosystem. Whereas in the former the direct outcomes are mostly the reduction of environmental hazards of existing productive activities, the latter opens up possibilities for directly influencing the generation of eco-innovative technologies, products and services, shifting technological progress towards different directions.

Systematic governmental efforts to boost eco-innovations are going to be critical to leapfrog unsustainable technologies and industrial behaviour. Governments have nonetheless been seen as reactive agents, responsible merely for mechanisms for command and control. A great variety of authors have argued that governments can be more proactive [24] in the promotion of eco-innovations, creating promising and integrated policies in areas such as industrial development, foreign trade, environment, science and technology and education [16], capable of fostering an ecosystem that allows green technological niches to flourish. Emerging countries, such as Brazil, can use public stimuli to eco-innovations as means to catch up, by absorbing, imitating technologies created elsewhere, as well as by creating proprietary innovations that will be converted into international competitive advantage in future.

Therefore, other studies covering public governance incentives to eco-innovation in emerging economies are essential to better understand how governments can simultaneously foster economic performance and a more resilient environment. Although not thoroughly investigated in this study, it is also important to shed light on other economic mechanisms that can boost eco-innovations and in what extent eco-innovative companies motivated by regulations made use of public economic instruments, such as subsidies and public funding helping niche-based innovations to compete against the prevailing and unsustainable technological alternatives.

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Evolutive Scenarios for a New Concept of Sustainable Mobility

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Abstract The present paper reports on an investigation of new mobility and manufacturing concepts, carried out in the framework of a research project funded by the Regional Government of Campania for an innovative development of the automotive supply chain. With reference to a new concept of sustainability that involves citizens and communities, the scenario depicted is characterised by an integrated innovation that affects people, new technologies and, generally speaking, as well as by the appearance of alternative models generated by individuals and by the small production realities scattered across the territory. Just like the manufacturing industry is increasingly moving towards new forms of production, the mobility sector is also undergoing deep transformations. It is with this approach of radical renewal that the present research tries to re-imagine the new systems of interaction and involvement of users—co-designed models, and digital manufacturing modes leading to the efficiency of services and production processes in the automotive sector.

Keywords Sustainability mobility · Social innovation · Digital manufacturing · Productive processes · Automotive industry

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1 Introduction

The research presented here is part of a wider project for the development of strategic manufacturing supply chains in Campania. The leading stakeholders include our DICDEA Department and the automotive Italian company Blue.

By adopting a Programme Contract for the development of strategic manufacturing supply chains it is possible to create an entirely sustainable and innovative virtuous cycle including information, design, prototyping and experimentation in the supply chain; in addition, this approach provides the concrete opportunity to trigger off positive, dynamic effects due to the fact that together, the enterprises have access to more advanced services than they could normally afford on an individual basis, as well as benefiting from collaboration.

More specifically, "the Sustainable Microcar" research project, in the framework of which the design and ergonomic testing of the seats presented here have been carried out, has the fundamental aim of continuous sharing and collaboration across levels within the automotive supply chain, generating continuous innovation thanks to the support of research bodies in collaboration with the enterprises. As Sennett points out, a dialogue with such a complex variety of subjects requires rules, codes, and communicative artefacts to enable the development of ideas by triggering off real integration and collaboration processes [1].

2 Sustainable Mobility and Models and Social Innovation

In the past few years, the debate on the issue of innovation and of the involvement of communities in urban regeneration processes has generated a number of design experimentations and the spreading of new urban mobility models. These envisage the participation of communities not only in the experimentation and testing stages, but rather in the creative process leading to the development of ideas and solutions concerning specific living places. Social innovation is descried as "innovation that is explicitly for the social and public good. It is innovation inspired by the desire to meet social needs which can be neglected by traditional forms of private market provision and which have often been poorly served or unresolved by services organised by the state. Social innovation can take place inside or outside of public services. It can be developed by the public, private or third sectors, or users and communities—but equally, some innovation developed by these sectors does not qualify as social innovation because it does not directly address major social challenges" [2].

This approach generates significant results in terms of possible change of communities' behaviours towards sustainability. The roadmap included in the White Paper considers actions at different levels: from policy-making to technological research and development; from incentives to measure aimed at increasing public acceptance of new technologies and transport management tools (…) A good awareness among the users and a good perception of the changes needed by the policy-makers and the producers are essential to drive the change we are all looking for" [3].

Clearly, the social component in creative processes has established and structured itself through the communities of citizens/users who share in the creation and development of products as well as in the provision of collaborative services. The level of participation has different implementation levels, from the one entailing the involvement in strategic policies to the bottom-up one, and up to the spreading of autonomous digital productions. As Ezio Manzini points out, a diffuse design [4] becomes widespread, involving people as carriers of abilities on the one hand, and experts who play the role of guides, of facilitators of a complex, and at times contradictory design process on the other. The intervention of expert design is thus crucial for its strategic and design value.

The setting in which this diffuse design ability can develop, consolidating existing networks or generating new collaborative organisations, as well as developing original solutions to social problems or needs, is a setting involving several actors: institutions, enterprises, communities, organisations, and designers. As Ezio Manzini points out, a dialogue with such a complex variety of subjects requires rules, codes, and communicative artefacts to enable exchange and the development of ideas by triggering off real integration and collaboration processes.

3 The Demand of Mobility and the Instruments for Sharing

The study of the constant evolution of habits in the human-machine interaction, the change of mobility and transport services, the evolution of internet technology and, in general, the dynamic nature of a service of social networking are preconditions for the setting up of innovative scenarios in which to experiment with alternative mobility models. The spreading of solutions to enhance sustainable mobility, systems to improve the logistics and distribution of commodities, technologies for environmental monitoring and for energy saving and efficiency are the themes on which, for a few years, projects have been developed and carried out at the urban scale, envisaging the active participation of citizens. The Italian and European experiences show that sustainable mobility projects and sharing models (car pooling, bike sharing, etc.) have become widespread, generating a positive environmental and social impact.

The spreading of services to citizens which impact the integrated management of the mobility supply, the spreading of information instruments for flow optimisation and the sharing of vectors, makes the new transport systems more and more linked to individual and collective choices.

Urban mobility is supported by the software and devices known as 'smartness tools', which make the mobility supply more and more tailored. The analysis of bigdata coming from transport users and operators makes it possible to identify in real time events such as accidents, traffic jams, service interruptions, and to devise different transport options. Mobile devices and social networking applications acquire information flows from several sources, the contents of which are generated by the users by means of crowd-sourcing systems so as to enable a conscious, tailored choice. The interaction generates the spreading of open technological instruments that are able to acquire and process information and to spread it across communities. By means of platforms, It tools can integrate data and information (online positioning data, traffic flow estimates, etc.); support integrated and inter-modal transport services; plan journeys providing users with information on costs, times, environmental impact and quality of service; identify any criticalities in the service provision; define mobility functions related to the variations in the preferences shown by the users.

The analysis and management models are concentrated on utility functions, and aim to convey information, which are typical of social networking services. Thus technological products, services and prototypes are developed, including web/mobile platforms, for incoming and outgoing information management.

The advantages of social networks and Data Analytics techniques provide the opportunity to identify orientations and topics of interest (topic and novelty detection) of homogeneous groups, the relationships between groups, the social influence, as well as to monitor the evolution and changes of the network and identify feelings and opinions (sentiment and opinion mining) [5] with reference to the quality of services offered. This information can orient the design of products and services and involve the communities that the mobility systems target in a more and more active manner. An interesting study has identified the importance of ‘urban narrative’ for the design of a ‘smart’ environment. The vision proposed in the paper consists in combining the data coming from networks of sensors with what the citizens report (storytelling), acting as moving ‘human sensors’.

By means of a web-based platform suitable also for mobile devices, the user can find, in one single interface and in real time, a set of information generated by the combination of different types of information concerning times, duration and itineraries of public transport, as well as services such as car pooling, car sharing e bike sharing. The information uploaded by the users themselves is spread through a social network but can contribute to generating new services too.

One example of this is the OpenStreetMap service, which makes it possible, by open access and thus with no intervention on the software developed, to implement the data in an autonomous, diffuse way. The aim of the project is to create and make cartographic data freely available at no charge, thus avoiding the problems due to legal or technical restrictions which prevent their free use for specific purposes.

In order to design innovative products and services and affect the communities’ attitude towards mobility choices, it is necessary to analyse the causes that generate the demand. Through the analysis of methodological approaches, i.e. the economic one—related to the idea of utility; the geographic one—related to the concept of accessibility; and the psycho-sociological one—related to the concept of individual motivation, it is possible to monitor the community's orientation and come up with consistent solutions.

The economic approach rests on the concept whereby every time an individual has to make a modality choice, s/he compares the various transport alternatives, and evaluates the utility of each. The choice of one particular solution among many is to the outcome of a rational process of maximisation and optimisation of benefits.

The geographic approach is based on the study of spatial factors and on the concepts of density and accessibility, therefore on the availability of access to means of transport other than private cars.

The socio-psychological approach is based on the analysis of the subjects' behaviour and habits and on the factors that affect their choices on matters of mobility, such as environmental awareness and socio-economic factors.

Integrated transport models are becoming more and more widespread, as they can rapidly adapt themselves to the changing conditions and needs as well as monitor data with the aim of suggesting new transport solutions in real time.

In Italy, projects such as TAM-TAM and TraffiCO2, have been developed, which—thanks to the support of mobile devices and software—analyse the contents generated by the community and offer solutions to the citizens' demands of mobility. The TAM-TAM project is an integrated platform for the management of the mobility supply, which develops solutions related to traffic de-congestion by proposing the optimisation of individual and collective choices. Starting from the study of travelling habits, from the identification of behaviour prediction models and the provision of services to citizens, the project offers a panel of information services, making it possible to assess the various public and private transport alternatives for the same journey, thus optimising mobility choices.

The TraffiCO2 project consists in the development of a social network for the management and regulation of urban flows, addressing mainly associations, agencies and companies. The whole system is based on exchange as a model of complementary virtual currency. The aim is to provide an efficient service, optimise mobility flows as well as increase awareness concerning ethical and sustainable behaviours, with reward-based systems linked to the volumes of CO_2 accumulated by individual choices in terms of mobility and games. The use of it devices gives access to information on travelling modes with indications concerning times, distance, cost, emissions and burnt calories.

4 The Evolution of Productive Processes Through New Technologies

As the new digital technologies are bringing about deep innovations in the relationship between people and their manner of movement, in the same manner these are changing the production of vehicles from the inside. In recent decades there has been, indeed, a deep renewal of the production system that has radically changed its location, time, and the interaction with consumers [6].

There has been a gradual shift from a manufacture of multiple identical items, to a manufacture of multiple different items, according to a renewed 1:1 productive relationship with man. Through the web, the product is now built directly by the community and for the community, changing as the the users who benefit from it change.

Technologies such as 3D scanning, 3D modeling and algorithm design give shape to new scenarios of Automotive Design, often undermining the old way to design and produce vehicles.

The invasive presence of social platforms and software which upload skills and information to the web facilitates a continuous innovation, for a production that changes quickly, precisely in relation to its changeable and diffuse nature.

Companies that manufacture limited series and build customized products, make the end user an active subject that participates, collaborates, and influences the logic of the market. The process is transparent and open. Machines, materials, and processes are made manifest, according to a new logic of collective knowledge development [7].

The new frontiers of digital manufacturing progress on the one hand with the development of 3D prototyping and, on the other hand, with the recent systems of collective interaction. They involve different disciplinary sectors, from Automotive Design to Social Innovation, from production Engineering to computer engineering. An example of this new vision is Local Motors, which in 2012 launched an international contest for a car project printed in 3D. Among the numerous participating projects, the winner was STRATI, which is a small electric city car, completely printed in additive manufacturing. However, the idea of Local Motors does not stop here. In 2015, the company built a social platform where everyone can reserve their own car at a very low cost and self-assemble it autonomously, anywhere [8].

The revolutionary idea is therefore to create a new system of micro-factories scattered across the territory, supported by the users themselves. In line with a B to B logic, the beneficiaries of this micro manufacturing reality are already part of the network. A productive system thus conceived, triggers a bottom-up pattern of consumption and turns the end user into an active subject that participates, collaborates, and influences the business's design strategies.

5 Innovative Digital Productions for Automotive Design

In the Automotive sector, the most advanced design-oriented research is pursuing new operational scenarios that reflect on the relationship between digital and physical, hand-made and machine-made, within new transdisciplinary fields. As a result of the digital dissemination, after a first pioneering phase, it is now at a turning point. Its use is currently more aware of its own tools in order to achieve a real reconciliation with the natural world.

Interesting paths come from a study of a complex manufacturing, hybrid supply chains, innovative technologies integrated with the traditional ones; mixes of craft and industry; digitalized excellence manufacturing.

Examples of this procedural amalgamation are in the work of designer Charles Douglas who, during the Clerkenwell Design Week held in London in 2012, adopted the use of chisels and manual tools to work with clay in order to achieve a better optimization of the shims and the shapes of a Jaguar car [9]. Following a careful study based on a handicraft model of the object, the new manufacturing process envisaged an industrial playback through a scan, and a 3D manufacture. The project named Jaguar Clay modelling thus implements a new type of procedural combination that allows a unique, unrepeatable formal research.

From a point of view more related to the new digital production processes, a union between innovative materials and advanced manufacturing techniques in the project makes a path of research strongly original. Many of these experiments require a further deepening through dedicated methodologies and ad hoc instrumentation which will only be engineered and made accessible on a large scale at a later stage. At the same time, they already clearly show the signs of a highly aware use of technology.

The Additive Manufacturing technology, which was first developed for the realization of small objects, is now increasingly invading the world of mechanical and production engineering. In the “3D opportunity in the automotive industry” research Mark Cotteleer and Jim Joyce clearly illustrate how the use of additive manufacturing can be transferred to the car industry through a diagram that explains all the possibilities, by breaking a normal car down into its individual components [10].

With the optimization of the processes and technologies of materials today it is possible to imagine a wider adoption of additive manufacturing in industry. Therefore the future of this development is the use of AM as the primary production technique for vehicles. A project that is experiencing this possibility is Urbee 2, which consists of an electric lightweight car that has as many as 50 parts produced with additive manufacturing techniques [11]. Specifically, the outer frame is made up of 20 distinct panels, which are produced through rapid prototyping for modelling and fused deposition (FDM). This is an extremely virtuous case, if you think of the huge number of components that generally make up a vehicle.

The lightening of the structures, instead, can be experienced in the project of the Joris Laarman Lab, called Microstructures, which attempts to evolve the process of 3D printing by testing a new parametric mode of deposit material [12]. The Dutch study, through the implementation of the Soft Gradient chair, conducts research on 3D printing in polyurethane, a material with exceptional characteristics in terms of strength-lightness. The polyurethane deposited in 3D works as foam, picked up depending on the needs of resistance, effort, robustness of the structures, is going to fill or empty spaces of the matter.

However, the study design of the materials and techniques sometimes investigates the digital and its manufacturing processes also through a mix of the disciplines of biotechnology or synthetic biology, looking at the vehicle as an organic, living structure. During the Design Festival held in London in 2014, the design magazine Deezen together with the car company MINI presented the exhibition: Frontiers: the future of mobility [13]. At the festival six designers were invited to design, including Alexandra Daisy Ginsberg, Keiichi Matsuda, Pernilla Ohrstedt, Matthew Plummer-Fernandez, Dominic Wilcox.

Among the various concepts presented, Ginsberg's project was the most visionary and interesting. The English designer offers a family of 112 miniature cars with the intention of creating an "ecosystem model" of vehicles. The idea is to imagine a future in which cars can be built using biological materials, coming partially from living human beings. In a future of sustainable biodegradable materials at affordable prices, car manufacturing appears as being more localized and differentiated, reflecting regional tastes and traditions. In order to achieve a tangible optimization of the project, Ginsberg is now working closely with scientists and engineers from the emerging field of synthetic biology, to investigate the possibility to build real cars that carry the genetic features of their users. In the current state, the project is obviously still a provocation, but it is very interesting because it opens up the boundaries of a research where design drops its industrial perimeters and opens up to new possibilities, which only a few years ago were considered utopian.

6 Conclusions

The closing work-project, demonstrative of the whole supply chain experimentation process, aims at designing and sharing innovative, ergonomically tested products in the automotive field. The aim of this work-project is knowledge gathering and sharing for the management of the whole project.

The project, which will close to its conclusion, is including now the following work-packages: the project management; the management and the optimisation of shared processes in the automotive supply chain; the supply chain information flow management and sharing; the design and the virtualisation technologies and systems in a shared environment; the industrial and car design systems.

The whole process takes place in an environment in which the pillars of the research project are collaboration, sharing, and environmental and social sustainability. Scenario research has supported the definition of a new concept of an eco-compatible micro car, currently under development, which brings together advanced prototyping technologies and design approaches informed by social innovation. In the design-oriented scenario that has been depicted, the new vehicle does not only comply with parameters such as modularity, transformability and possibility of equipment, but investigates the demand of innovation at large, analysing the social relations of users and their movements in space, in line with a human-centred approach. The ongoing research is focused on defining a global, integrated strategy involving, on the on hand, the users in their mere use of the vehicles and, on the other hand, industry, for what concerns the innovation of technologies and sustainable production processes. Hence a new idea of mobility, resulting from a variety of relations and parameters which, although extremely heterogeneous, interact with one another.

The project aims at achieving the following results:

- Set up a dialogue between research bodies and local production entities, in which the reference role of research in local development is acknowledged;
- Support the competitiveness of enterprises through design-oriented methodologies with a view to the overall sustainability of design and production process;
- Test new digital production models to devise new products and services;
- Consolidate the practices of diffuse design involving the communities in all the stages of the creative process.

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Implications of Open Source Design for Sustainability

Jérémy Bonvoisin

Abstract In order to cope with the challenges of sustainability, systematic methods have been developed for improving the ratio between usefulness and environmental impact of products. These necessary efforts are however constrained if the surrounding business model patterns are not challenged at the same time. In this article, open source design (OSD) is presented as a potential concept leading towards alternative and eco-efficient production and consumption patterns. Potential advantages of OSD for environmental sustainability are hypothesized and confronted with the analysis of the environmental friendliness of four open source products. Two synergies between sustainable design and OSD are identified (product modularity and design for local manufacturing) as well as corresponding challenges for further research.

Keywords Open source innovation · Open hardware · Sustainable product design · Eco-design

1 Beyond Sustainable Product Design

Eco-design, i.e. the approach of improving the ratio between usefulness and environmental impact of a good or service is a necessary approach to assume the challenges of sustainability and has been largely addressed in engineering design in the last decades—see, for example, contributions of Wimmer and Züst in [1] or Pigosso et al. in [2] for an overview of this domain. This product focused approach may be limited if production and consumption patterns remain unaddressed at the same time. Improvements in terms of environmental impacts per product unit are framed by several constraints applying to product development (in terms of, among other, performance, production cost, aesthetics, and standardisation) [3]. A mere

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product-centred approach may not allow achieving more than incremental improvement though radical cuts in the environmental impacts of our material economy are required. Therefore, while keeping the pace of increasing maturity of eco-design, complementary approaches are required to question not only the technical design of the product but also the production and consumption pattern in which it takes place. One promising complementary approach is the concept of Product Service Systems (PSS): an integrated offer of products and services focused on customer satisfaction rather than on exchanging product ownership (e.g. Tukker and Tischner [4]). While it is meanwhile understood that PSS are not inherently eco-efficient, this concept has been identified as a "potential sustainable business model" because it may help break the links between profit and production volume without constraining usage volume [5].

In this essay, open source design (OSD)—an innovative approach of product development and manufacturing tending to redefine the roles of the producer and the consumer—is presented as an alternative concept for challenging conventional production and consumption patterns. In a first theoretical section, the concept of OSD is defined and potentials for leading to eco-efficient production and consumption patterns are hypothesized. This discussion is followed by an empirical analysis of four OSD projects with the help of a qualitative environmental analysis grid presented. Theoretical arguments are confronted to empirical data in order to draw conclusions on the potential of OSD for supporting environmental sustainability and to identify challenges for further research.

2 Open Source Design, Definition, Challenges, Potentials

The spread of information and communication technology and cheap low-size production tools like 3D-printers enabled the emergence of the "maker movement" [6] based on the extended participation of the individual citizen in product definition and production. A new category of "home engineers" is supported by online CAD model repositories like Thingiverse[1] or Shapeways[2] that allow up- and downloading 3D models that can be printed at home or received per post. Those repositories allow their users getting inspiration, exchange best practices and do-it-yourself assembly manuals. The easiness of sharing digital content also enables local-based projects to publish online product-related information so their product can be copied or further developed by spontaneously emerging online communities, like in the case of the well-known RepRap 3D-printer.[3] Companies may also use the dynamics of online communities and open source product definition for setting up innovative business models. Examples are Local Motors,[4] a car

[1]http://www.thingiverse.com/.
[2]http://www.shapeways.com/.
[3]http://reprap.org/.
[4]https://localmotors.com/.

which is registered under a Creative Commons license and which is manufactured in distributed workshops, or the open source electronic board BeagleBoard[5] produced by Texas Instruments™. The current emergence of such initiatives based on open source products shows great potential for product innovation and incubation of new businesses, and further, allows OSD to be seen as a potential "billion dollar business" just as open source software became along the last 40 years [7].

2.1 Characterizing Open Source Design

Just like open source software development, OSD is a form of open source innovation, defined by Raasch et al. [8] as the "free revealing of information on a new design with the intention of collaborative development of a single design or a limited number of related designs for market or non-market exploitation". Huizingh [9] differentiates product development projects depending what is being made open: either the development process itself (i.e. by giving the opportunity of every interested person to participate) and/or its outcome (i.e. by publishing product information). The case where both elements are closed is conventional industrial product development, while where the process is open but the outcome closed is crowdsourcing. OSD, as defined in this article, is the case when both elements are open. Balka et al. [10] further refines the concept of openness as a gradual and composite concept determined by three factors: transparency (access to sufficient information to understand the project details), accessibility (possibility for community members to take an active part in the development) and replicability (possibility of self-assembly of the product). Combining these definitions, the concept of OSD can be characterized by:

- a participatory approach allowing the involvement of every interested person;
- the willingness to share intellectual property related to a physical product under the four principles of open source (right to see, use, modify and redistribute [11]);
- the possibility to replicate the product, i.e. that a different team than the originator team fabricates the product.

As illustrated by the examples cited at the beginning of this section, different types of approaches may satisfy this definition. In practice, OSD projects may be delineated according to the following characteristics:

- Level of openness. Products are not either completely open or closed, but in practice partially opened, like in the case of the Arduino[6] electronic board. Companies may choose to publish some parts in order to profit from the dynamics of the crowd and keep some parts protected in order to safeguard key competences [10].

[5] http://beagleboard.org/.

[6] https://www.arduino.cc/.

- Size of the active community. There is a continuum between a one-man or one-company project whose documentation is made open source and a large community designing a project from scratch. Participants in open source projects may be characterized in three types of roles (as assumed e.g. in [12]): (1) the deeply involved core team of developers who takes an active part in generating content and organizing the development process (2) a pool of contributors who may generate content in a rather sporadic way and (3) a larger audience who follows the development of the project and is interested in using results without taking part actively. The size of the active community is resulting from the absolute size of community and the relative size of these three groups in the community.
- These characteristics may move along the project timeline. Some projects may for example start as a local project, go open and community-driven and turn back to partially closed, as the famous example of MakerBot™ illustrates.

2.2 Challenges for Further Development

As a disruptive alternative to current practices, OSD raises numerous challenges for practical implementation. For example, in contrast to industrial product development, contributions of project members are no longer sealed by contractual agreement. Hierarchical organization is therefore replaced by a low level of restrictions, self-motivation and self-selection of tasks [13]. To date, the emergence of OSD still suffers from a limited availability of adapted structuring mechanisms helping to face the organizational challenges raised by distributed collaboration of non-contractually engaged volunteers. A large part of OSD projects is still restricted to the development of products of low complexity and quality, i.e. prototypes or toys for do-it-yourself hobbyists [14]. In order to compete with today's industrial standards, OSD shall be provided with engineering methods and tools ensuring significant process efficiency [15]. Another challenge is to, based on existing (un-)successful examples, define systematic guidance for developing business models generating economic value out of open source products. Further, the non-exclusivity of the participation in the development process requires protection mechanisms against vandalism, as experienced by Wikipedia [16] or other participative projects (e.g. [17]).

2.3 Potential of Open Source Design for Environmental Sustainability

Open source innovation (including open source design and software) is seen as an alternative to the innovation model based on protection of intellectual property through patenting, whose ability to foster innovation has been criticized [18]. By enabling any interested person to take part in solution finding, open source innovation may allow mobilizing sufficient creative task force so innovation becomes “trivial”. In other words, open source innovation is believed to lead to:

- Better design due to high number of peer reviews and knowledge capitalization;
- Faster adoption of technologies thanks to lower financial and knowledge barriers;
- Especially for companies: reduced R&D costs and development time due to the involvement of a higher number of (voluntary) contributors;

From a social point of view, a fundamental motivation of the maker movement is to defend user autonomy, i.e. the capability of the citizen to influence the products (s)he is surrounded with. This is notably expressed by a wished independency to industrial manufacturers regarding product repair: being able to repair a product on ones’s own and even to participate in the design process in order to prevent planned obsolescence. In environmental terms, a first hypothesis (H1) is that OSD could lead to longer service life due to promotion of robust product design and repairability.

In parallel to this, the maker movement is motivated by an ideal of “do-oracy”, where “makers”, in contrast to “consumers”, have access to decision power through their creative/constructive activity [10]. From a very broad perspective, this ideal challenges the concept of social distinction through conspicuous consumption and even gives rise to a hypothesis of reduced consumption volume (H2). On a more concrete level, this ideal is expressed by the principle of “do-it-yourself” that supports the generation of more locally-bound value creation chains and the concept of distributed economy as presented for example by Johansson et al. [19]. From an environmental perspective, locally-bound value creation chains may go along with use of local resources, hence promoting shorter transportation loops, adaptation to the local ecosystem and even closed-loop material circles (H3). Finally, the participation of the end-user in design may support better fitting between the product and the user’s needs (H4). From an environmental perspective, better adaptation means avoidance of over-engineering and corresponding useless environmental burden, as well as a closer emotional link between the user and the product promoting longer product life.

3 Empirical Research—Case Studies

Some of the hypotheses presented in the previous section include socio-economics effects and their verification would require a long series of observations that are out of the scope of engineering design science. Therefore, in this section, the empirical analysis is limited to concrete and technical observations: how products developed in OSD projects integrate aspects of environmental friendliness and what is being claimed by the communities developing those projects.

3.1 Methodology

Four OSD projects have been selected that satisfy the three criteria of openness defined by Balka et al. [11] and introduced in Sect. 2.1: transparency, accessibility and replicability. Translated in practical terms:

- Product information is at least partially available online through e.g. CAD Models, Bill of Materials (BOM) or assembly instructions.
- The project is surrounded by a community that is at least passively following the development and ideally actively involved with encouragement from the originators/moderators of the project.
- The product has been at least been prototypically realized or ideally already replicated, i.e. produced by another team than the core team of originators.

The evaluation of the environmental friendliness of the selected products is based on the analysis grid offered by the "ten golden rules" of eco-design developed by Lagerstedt and Luttropp [3] (and reproduced by Table 1). The online documentation of the four selected projects has been reviewed in order to identify how far these ten generic design principles (that cover the whole product lifecycle) are satisfied by these products according to their documentation.

3.2 Analysis of the Four Selected Projects

LifeTrac 6 is an open source tractor developed in the frame of the project Open Source Ecology, a project aiming at developing and building a "Global Village Construction Set", i.e. a set of 50 open source industrial machines allowing to "build a small civilization with modern comforts".[7] Six versions of the tractor have been developed over time and four of them have been prototyped. The third version has been replicated at least 3 times. Product information (CAD models, BOMs, manuals and videos) is available without registration on the wiki of the project which is being used as a development and documentation platform for the whole project together with forums and a self-developed website. Intellectual property is licensed under an extended Creative Commons license (CC-BY-SA 4.0 Attribution and ShareAlike).

The product is designed to be "simple" to assemble in order to allow do-it-yourself, hence local production. This is achieved through the use of standard Lego-like parts that can be assembly by bolts. The product is further designed to be modular so it is easy to maintain, repair and upgrade, therefore supporting its durability. Modularity is achieved by ensuring disassembility through reversible connections (e.g. bolting of XYZ connections) and interchangeability of general

[7] http://opensourceecology.org/.

Table 1 Analysis grid adapted from Lagerstedt and Luttropp [3]

Begining of life	*Use of recycled/reused raw materials and components*. Do not use toxic substances and utilize closed loops for necessary but toxic ones
	Use of non-toxic raw materials. Minimize energy and resource consumption in the production phase and transport through improved housekeeping
	Lightweight design. Use structural features and high quality materials to minimize weight in products if such choices do not interfere with other functional priorities
	Minimized transportation. Minimize energy and resource consumption in the usage phase, especially for products with the most significant aspects in the usage phase
Middle of life	*Minimized energy and resource consumption in use phase*. Promote repair and upgrading, especially for system-dependent products. (e.g. cell phones)
	Repairability and upgradability. Promote long life, especially for products with significant environmental aspects outside of the usage phase
	Durability. Protect products from dirt, corrosion and wear, thereby ensuring reduced maintenance and longer product life
	Maintainability. Prearrange upgrading, repair and recycling through accessibility, labelling, modules, breaking points and manuals
End of life	*Recycling and reuse*. Promote upgrading, repair and recycling by using few, simple, recycled, unblended materials (e.g. no alloys)
	Reversible joining elements. Use as few joining elements as possible and adapt them according to the life cycle scenario

purpose parts (i.e. components can be used in other products). Modularity further supports recycling and reuse as well, hence resource efficiency.

Multimachine[8] is an open source multiple-purpose machine tool that is designed to be assembled by a non-expert using commonly available tools out of discarded vehicle parts. In its current version, it is a 3-in-1 machine providing the functions of drill press, lathe and milling machine. It is however intended to design the product as a platform for more tools. The project has been developed as a one-man activity and made open source via an online group. 80 pages of assembly instructions can be downloaded from the project website. No information about licensing could be found.

The very concept of a product made of discarded car parts shall ensure the sustainability of material procurement. The product is designed to be built "at home", hence for local production. The concept of extensible machine tool platform shall ensure upgradability and integration of new or updated machine tool functions using rotating elements (e.g. grinding). Modular design shall ensure easy maintenance with commonly available tools as well as reuse of parts.

WikiHouse is an open source house building concept based on decentralised manufacture of wooden structural components. Structure components can be produced locally by CNC machines and assembled by man force and without

[8] http://opensourcemachine.org/.

specialized training and specific tools. The project was started in 2011 and a legal entity was created in 2014 in order to support a global online community that further develops the project. More than 10 versions of the WikiHouse have been adapted and built throughout the world to date. Product information (e.g. CAD Models and building plans) is licensed under a CC-BY-SA license and is available online; the community communicates over a Google Group and shares data over a GitHub repository. A version of the product as a prepared kit is commercially available in the UK.

The project claims to use sustainability-sourced timber and materials with low embedded carbon, though this is less a design property than a question of production context. It is designed for local production: the models can be downloaded and parts can be milled using local CNC machines and bolted together on-site. Energy in the use phase shall be saved thanks to high insulation capacity of the material used. Here again, modularity shall ensure that building elements are dismountable and substitutable, thereby supporting maintainability and durability.

RepRap (for "Replicating Rapid-Prototyper") is a general purpose "self-replicating" desktop 3D printer initially implementing the process Fuse Deposition Modelling. The machine is claimed to be self-replicating because it can print some of the structural parts required for building a new machine. Several forks of this project have been developed since the release of the first functional machine in 2007. We consider here especially the model named "RepRapPro Mendel". The project and its different variant are further developed by an active community structured thanks to several online resources (wiki, forums, IRC, GitHub repository, mailing lists). Intellectual property is licensed under GNU General Public Licence. More than 50 vendors are selling starter kits for building a RepRap.

The printed mechanical parts used in the structure of the machine are made of PLA (Polylactic acid), a thermoplastic that is claimed to be recyclable and biodegradable. The machine is designed so structural parts can be locally produced and the whole product can be locally assembled as well. Modular design and disassembility ensures maintainability, repairability, upgradability and recyclability, hence supporting product durability and resource efficiency.

Table 2 summarizes the analysis of the four considered projects. A first observation is that the three criteria use of non-toxic raw material, lightweight design and minimized transportation are not addressed by any of the selected projects. Minimized transportation is however indirectly covered by the fact that all the considered products are designed to be manufactured locally. Nonetheless, the potential environmental advantage of reducing transportation through local production patterns is not directly claimed by the selected projects. Minimized energy and resource consumption in use phase is only under the focus of WikiHouse and is not addressed by any other projects. Use of recycled/reused raw material and components is also only directly under the focus of Multimachine. LifeTrac and RepRap indirectly address this issue by providing the possibility to integrate reused parts.

In contrast to this, all projects are designed to be maintainable, repairable and upgradable. On one hand, this is achieved through modularity and the use of

Table 2 Summary of analysis of the four selected projects

	Evaluation criteria	LifeTrac	Multimachine	Wikihouse	RepRap
Begin of life	Use of recycled/reused raw material and components		x		
	Use of non-toxic raw material				
	Lightweight design				
	Minimized transportation				
Middle of life	Minimized energy and resource consumption in use phase			x	
	Repairability and upgradability	x	x	x	x
	Durability	x		x	x
	Maintainability	x	x	x	x
End of life	Recycling and reuse	x	x		x
	Reversible joining elements	x		x	x

reversible joining elements and on another through the availability of detailed product information. Three of the four projects claim their products to be durable based on this analysis.

3.3 Interpretation of Results

This empirical analysis underlines two general tendencies. On the one hand, OSD projects do not necessarily seem to focus on environmental aspects related to product beginning of life. On the other hand, the concept of open source product design seems to be strongly connected with environmental aspects related to the middle and end of life: maintainability, repairability, upgradability, reusability, recyclability and therefore extended product life and increased resource efficiency.

This analysis also brings to the foreground two concepts shared by all projects and that are of potential interest for environmental sustainability: product modular design and design for local manufacturing.

All four analysed projects claim to have designed modular products. The concept of modularity is technically implemented through the use of reversible connectors actionable with conventional tools and allowing for replacing a damaged module (repairability), integrating a new functionality (upgradability), and exchanging modules between products (reuse and recyclability). This last point is also addressed in the case of LifeTrac through the use of Lego-like standards components. It has been previously empirically observed that product modular design plays an important role in open source product development projects because it supports the necessary self-selection of tasks required by a non-hierarchic organization of work [13]. The present study underlines that modularity is also being used by open source product design projects as a tool for claiming sustainable product design.

Another predominant aspect is the focus on local production. This is achieved, for example, by use of local material flows (e.g. scrap in the case of the Multimachine) as well as by "simple design" (as advocated for example by LifeTrac) that can be assembled by non-experts or even amateurs thanks to standard interfaces (e.g. bolts in the case of WikiHouse). How local can the production be and what relative environmental advantages (e.g. less transport) or drawbacks (e.g. less concentrated, hence less efficient production) it may confer to the product is however not clear.

4 Conclusion

This article provides a first attempt to define the potential of open source design for environmental sustainability. The limited size of the study does not allow drawing general conclusions, but already gives directions for further research. Of the four hypotheses formulated in Sect. 2.3, two have been supported in the empirical study: that open source projects promote repairability in design (H2) and aims at generating locally-bound value creation chains (H3). Two product design principles constituting synergies between OSD and sustainable product design have been thereby highlighted: the use of modular structure and the design for local production. Based on these findings, research topics of interest for environmental engineering would be to determine (1) how beneficial local manufacturing could be for the environment (2) what design features enable local manufacturing (3) what practical product modularization methods help to make the best of the organisational and environmental advantages of product modularity. In order to refine the results of this first study, a further step could be to perform a larger scale analysis including a higher number of projects (allowing ensuring statistical representativeness), a more profound analysis of the projects (reflecting the history of their community and their degree of openness) as well as a deeper feature-based technical analysis of products.

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Sustainable Supply Chain Management in a Circular Economy—Towards Supply Circles

Anna Aminoff and Outi Kettunen

Abstract In the last few years, the circular economy has attracted increasing attention as a way to overcome the problems of the current production and consumption model based on continuous growth and increasing resource throughput. A circular economy is an industrial system that is restorative or regenerative by intention and design. Although supply chains are the key unit of action in the change towards a circular economy, the academic literature on supply chain management approaches in a circular economy is very much in its infancy. However, two distinct literature streams, namely sustainable supply chain management and product service systems, seem to offer valuable insights into the investigation of supply chain management in a circular economy. The aim of this paper is to analyse the main characteristics and challenges of supply chain management in a circular economy and identify how these two literature streams can contribute to researching it.

Keywords Supply chain management · Circular economy

1 Introduction

If the current consumption trend continues, the Earth's carrying capacity will be exceeded fivefold by 2050. The price volatility of natural resources is increasing and non-renewable resources are diminishing [1, 2]. Recently, the Circular Economy (CE) has attracted growing interest as a way to overcome the problems of the current production and consumption model based on continuous growth and increasing resource throughput [3]. CE refers to a concept that aims to create an industrial system that is restorative by intention. The CE discourse has recently

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started to emphasize the economic aspect, seeing CE business models as enablers to create a competitive advantage [2, 4–6]. The circular concept is estimated to give an even greater competitive edge in the future because it creates more value from each unit of resource than the traditional linear 'take-make-dispose' model [1].

Supply chains have been identified as a key unit of action in the change towards a CE, as collaboration between customers, suppliers and other stakeholders can keep used products, components and materials in circulation [1]. New business models may, for instance, rethink ownership and create new requirements and challenges for supply chain management (SCM). Thus, it is important to integrate SCM research into a CE. To the best of our knowledge, however, publications focusing on supply chain modes for a CE are still scant. In parallel, academic and business sector interest in sustainable supply chain management (SSCM) has risen considerably in recent years, which can be seen by the number of journal articles published [7, 8]. There is a strongly growing need to integrate environmentally sound choices into SCM research and practice [9] by reducing unintended negative impacts on the environment from production and consumption processes. At the same time, the discourse in product service systems (PSS) has attracted increasing attention from sustainability researchers, the rationale being that if companies focus on final user needs or the service a user wants rather than the product, it will be easier to design need-fulfilment systems with fundamentally lower impacts [10].

The aim of this paper is to analyse the main characteristics and challenges of SCM in a CE and to identify how these two literature streams, namely SSCM and PSS, could contribute to SCM research in the context of a CE. This is a preliminary study that aims to create a basis for a large empirical case study about SCM in a CE.

2 Method

This paper presents the results of a preliminary study. We combined a literature review with interviews and focus group discussion. When conducting the literature review, we combined searches from databases and snowballing. For the purpose of this preliminary study, we chose a qualitative study design to match the state of the current theory and the exploratory goals of the study. A focus group discussion was undertaken to gain an initial contextual understanding of the topic, and focus was on the challenges of companies to implement a CE. It lasted 2 h and had 8 participants. The participants were managers in the companies who had at least some experience of CE business models. To find suitable interviewees, we used theoretical sampling [11]. Our criteria for choosing interviewees from companies were based on: (a) interest in developing a CE, and (b) already having at least some experience of CE business models, since these informants are more likely to provide valuable information for our purposes. Data collection is currently ongoing. So far we have had 9 interviews with 19 informants. The interview guide relies on open-ended questions, and aims to get in—depth understanding of the theme. All interviews are recorded and transcribed verbatim to increase the findings' reliability

[11]. One interview takes about 2 h. The interviewed companies included waste management, crowdsourcing transportation and delivery logistics companies, a recycling social enterprise, a producer of recycled material-based products, and four shopping centres.

3 Literature Review

3.1 Literature of Circular Economy

CE is commonly defined as an industrial system that is restorative or regenerative by intention and design [1, 12]. So far much different kind of reports and articles about CE has been published. Most of these are non-academic, and a large number of studies concern the implementation of CE in China. The concept of circular economy traces back to different schools of thought [3, 13], but the research on CE implementation has been and still is mainly rooted on the industrial ecology. However, the industrial ecology researchers seem to focus on the benefits in terms of physical rather than monetary flows [3], and more knowledge is needed from a business perspective.

In a CE, new business models are developed to reduce the need for virgin raw materials. The basic approach of a CE is to eliminate waste by designing out waste. Products are designed and optimized for a cycle of disassembly, reuse and refurbishment, or recycling, with the understanding that economic growth is based on reuse of material reclaimed from end-of-life products rather than extraction of resources [4]. A key aspect is that material resources circle in short cycles (e.g. with minimum transportation, as local as possible), in which the material is kept as pure as possible (for ease of reuse) and the quality remains as high as possible over the longest time possible [3, 4]. In a CE, the concept of *user* replaces that of *consumer*. Unlike today, when a consumer buys, owns and disposes of a product, in a CE, durable products are leased, rented or shared whenever possible [4]. If goods are sold, new models and incentives motivate consumers (users) to return or reuse the products or their components and materials at the end of their primary use. New innovative business models, when changing from ownership to performance-based models, are instrumental in translating products designed for reuse into attractive value proposals.

Despite the huge opportunities, there are many barriers to the transition, including current product design and supply chains, and cultural resistance and mind-sets [4]. The challenge is that economic gain can only be realized if multiple players across business and research collaborate and reconceive key material flows and manufacturing processes, supported by policymakers and innovations [1, 14]. Today, the implementation of a CE is in the early stages and seems to focus on recycling rather than reuse [3]. The lesson learned from best practice examples is that the transition towards a CE needs the involvement of all actors in society and their capacity to link and create suitable collaboration and exchange patterns [3].

3.2 Literature on the SCM Aspects of a CE

Supply chains are the key unit of action in change towards a circular business [14, 15], and several publications and case studies report on the importance of SCM. However, based on our analysis of the extant CE literature, there appears to be a knowledge gap in terms of SCM. Here, we refer to some of the latest, non-academic publications—in the absence of academic ones—to give a picture of the SCM characteristics of a CE. We identify some common characteristics of SCM. However, just as circular business models and value chains may look very different in different industries, the characteristics of SCM may also vary.

Collaboration with suppliers and customers can keep used products, components and materials in circulation. The value in a CE is created by looping products, components and materials back into the value chain after they have fulfilled their utility over the life of the product [4]. Analysing the best practice business cases shows that an SCM approach that balances the forward and reverse loops and ensures uniform material quality is critical to success. According to EMF [1], tangible outcomes can be reached through joint action. Co-operation between supply chain partners, including cross-industry co-operation, is a prerequisite for enabling systemic change. It is also essential to take into account the global aspect and partners from several countries, as the supply chains often extend across borders [16].

Circular supply chains draw a sharp distinction between owning a product and having access to it, and between using materials and consuming them. Circular supply chains often promote the use of a 'functional service' model in which manufacturers or retailers increasingly retain ownership of their products and, where possible, act as service providers, i.e. they sell the use of products, not their one-way consumption or ownership [14, 17]. This creates new requirements for SCM. The open loops will close and the role of the opposite loop will grow, as today, reverse flows are significantly influenced by the high cost of collection and leakage from the system [14]. This opens a huge number of business opportunities for both 'old' and new players. In a CE, consumers become an active and central part of the supply chain by providing information to the system [17]. These changes influence the SCM to a great extent. Consumers have already started to require transparency throughout the supply chain and advocate responsible products and business practices.

Today's supply chains do not support the transition towards a CE, however, and one main barrier to the transition towards a CE is linear lock-in [1]. According to EMF [1], the challenge of closing material loops and regenerating natural assets is product complexity and supply chain length. The transition towards a CE can begin once the hinge points are identified and acted upon in a concerted effort across companies and along the supply chain [1]. Implementing circular business models requires a better understanding of the archetypes into which supply chains fall. Although the implementation of a CE is still in the early stages, circular supply chains are already in place in fibre streams such as paper and cardboard. According to EMF [1], the key to other raw materials following suit is being able to reduce the costs of establishing reverse cycles. There are trends that favour this: urbanization, advanced tracking and treatment technologies, and government stimuli. These require deeper investigation of the possibilities SCM can offer.

3.3 Literature on SSCM

The growing interest in SSCM is due to the fact that, in addition to demands for strong economic performance, organizations are now held responsible for environmental and social performance by main stakeholders [18, 19]. In the last decades, SSCM theories have been emerging, seeking to integrate environmental concerns into organizations by minimizing material flows or reducing unintended negative consequences of production and consumption processes [5, 9, 20]. However, more recent contributions have had a more holistic approach and take the whole product supply chain into consideration, emphasizing reuse and remanufacturing [21, 22].

One stream of literature on SSCM is reverse supply chains. This stream adapts CE principles to supply chain management, as a reverse supply chain includes activities dealing with product design, operations and end-of-life management in order to maximize value creation over the entire life cycle through value recovery of after-use products either by the original product manufacturer or a third party [21, 23, 24]. Reverse SCM, in its general forms, starts from the end-users (first customers) from whom the used products are collected and then attempts to manage end-of-life products through different decisions, including recycling, remanufacturing, repairing, and, finally, disposing of some used parts [23].

Reverse SCM is part of closed loop supply chain management (CLSCM). Based on the definition by Guide and Van Wassenhove [25], CLSCM is the design, control and operation of a system to maximize value creation over the entire life cycle of a product with dynamic recovery of value from different types and volumes of returns over time. Some authors make a distinction between open-loop and closed-loop SCM [24]. Open-loop supply chains involve materials recovered by parties other than the original producers who are capable of reusing these materials or products [26]. Closed-loop supply chains deal with taking back products from customers and returning them to the original manufacturer for the recovery of added value by reusing the whole product or part of it [27]. However, this classification doesn't seem to be well established in the literature. Due to the benefits of closed loop supply chains, some manufacturers have been placing a strong emphasis on achieving sustainable production by shifting from linear solutions to whole life cycle assessments and integrated environmental strategies and management systems [24].

More recent approaches of CLSCM emphasize the business view instead of other factors like legal, social responsibilities, or even operational and technical details [23], and that returns can be a value creator rather than a cost of business, as they can save the environment, and provide critical resources and customer value [28]. This approach definitely makes the research on CLSCM valuable to CE research. In their recent extensive literature review, Govindan et al. [23] identified multiple themes of reverse logistics, which seem to be useful in the context of a CE. The themes include: (1) Designing and planning: the aim is to determine strategic decision variables, like locations and the capacity of facilities, (2) Planning, including the number of flows between supply-chain network entities known as mid-term decision variables, (3) Price and coordination: important discussions between two entities of a supply chain network (for instance, a remanufacturer and a retailer of a second market) determine the price of products and coordinate win-win strategies to balance profit margins, (4) Production planning and inventory management (5) 3PL selection and vehicle routing problems

With a few exceptions, the literature on SSCM, including CLSCM, has focused on manufacturing industries [29]. Hassini et al. [27] suggest that this may be due to traditional operations research having focused on production and manufacturing topics and thus it is quite natural that SSCM researchers build on that literature. The contributions on the roles of consumers and B2C business are quite limited.

3.4 Literature on Product-Service Systems

Product-service systems (PSSs) are a specific type of value proposition that a business (network) offers to—or co-produces with—its clients [10]. Tukker and Tischner [30, p. 1552] defined PSS as 'PSS consists of a mix of tangible products and intangible services designed and combined so that they jointly are capable of fulfilling final customer needs.' PSSs have attracted attention from sustainability researchers, the rationale being that if one were to focus on final user needs or the service a user wants, rather than the product, it would become much easier to design need-fulfilment systems with radically lower impacts. In product-oriented business models, firms have the incentive to maximize the number of products sold [10]. In service-oriented business models, the incentives are different, as firms make money by being paid for the service offered, and the 'material products and consumables that play a role in providing the service become cost factors' [10, p. 76]. Previous literature has identified various business drivers for a successful PSS [31]. However, it seems that PSS business models can be complex to design, test, implement and bring to the mainstream [31, 32]. The user- and result-oriented PSSs have high potential for circularity, as circular business models emphasize use and service instead of ownership.

Although much research mentions the importance of SCM to the implementation of PSS business models, previous literature is quite limited on SCM-related issues. As an example, Lockett et al. [33] emphasize the need for a properly functioning PSS supply chain in which all the partners share relevant information and have aligned incentives and balanced benefits. Moreover, as the discourse on PSSs has focused on B2B manufacturing firms, the understanding of transforming the ideas of PSSs into the B2C context and the effect of this on SCM is still very limited.

However, as in a CE, new innovative business models for changing from ownership to performance-based models are instrumental in translating products designed for reuse into attractive value proposals, new knowledge on PSS in a B2C context is needed.

4 Results

4.1 Findings from Empirical Data

Based on the empirical data, we identified the business sector interests in SCM related to CE business models, as presented in Table 1. We categorized the interests

Table 1 Identified business sector interests in SCM in a CE

Topic	Empirical findings
Warehousing, collection and handling	The needs and requirements for warehousing • What are the needs for a warehouse or a "physical node" in online recycling? (2,5) • Where to store and separate the recycled material? (1,3,5) The new innovative solutions for warehousing in CE are needed • Possibilities offered by intelligent mobile warehouses (e.g. containers) (2,3) • Shared warehousing facilities would be cost effective for waste, recycled material and remanufactured goods (4) Decreasing handling costs; • Work force cost is high and this radically reduces the possibilities for handling the recycled material. (2,3) • Designing the (also remanufactured) goods so that transportation and handling could be cost-efficient at all phases of the chain. (4)
Reverse logistics: recycled material transfer from consumers and companies	New logistics solutions for consumers: • Role of crowdsourcing in transferring the products c2b, c2c, b2c and b2b. (2,3,5) • New logistics solutions that would motivate consumers to bring in recyclable material (1,3,5) The amount of waste varies a lot, and this causes problems at all phases: at the waste containers, at the facilities of a remanufacturer and at waste processing plants. (4) Efficiency of reverse logistics • Cross-sectoral co-operation in transfers (e.g. online stores and public sector). (2,3) • How can reverse logistics be made efficient in rural areas? (2,3) • How to make the transportation capacity and equipment of deliveries and return logistics match? Regulation sets some challenges. (2)

(continued)

Table 1 (continued)

Topic	Empirical findings
	• Building "villages" where waste and recycling material is transferred, and where there are remanufacturers for several reusable materials. The villages should be close to origin of waste in order to avoid excess transportation. (4) • Involving a larger network of transportation and waste management companies to be able to share resources, by e.g. digital services. (1,4) Ownership of waste material, who owns waste/material? (2,4)
Role of digitalization	Consumer's participation • How can digitalization facilitate consumer's participation in recycling and other CE activities? (1,3,5) • What is the role of tracking and tracing in motivating the consumers, e.g. by measuring the separation and analysing CO_2 impact. (3) • Real time information about available second hand goods would increase their reuse. New innovative solutions are needed (2,3) Efficiency • How can tracking and tracing be utilized in the supply chain to enable more efficient waste collection and separation? (1,4) • Monitoring the filling rate of waste containers, Waste type recognition with a camera, or IoT (1,4)
Network involvement	Role of outsourcing as a facilitator in involving stakeholders in CE business models in different operations of the supply chain: R&D, transportation, waste processing, production and marketing. (4)
Consumer role and C2C trade	Consumers' role in controlling the SC, enabled e.g. by novel digital solutions. Services and incentives for consumers • What kind of incentives and facilities do consumers need in order to separate waste and bring in recyclable material? (1,2,3,5) • Smart services that are easy for the customer and fulfil his needs as a whole. Recycling should be made very easy for the consumers. (2,3,5) • Categorizing consumers so that it would be possible to service them (3) C2C trade: What business opportunities does it offer for companies? How can the warehousing and transportation be organized? Logistics services are lacking. (2,5)
Influencing everyday practices of stakeholders	Role of rapid experimentations in giving information concerning possibilities to influence everyday practices of stakeholders. (1,2,5) Defining the factors of a positive CE image related to SCM. (1,5)

into following categories (1) Warehousing, collection and handling, (2) reverse logistics: recycled material transfer from consumers and companies, (3) role of digitalization, (4) network involvement, (5) consumer role and C2C trade, and (6) influencing everyday practices of stakeholders. The numbers in the end of each line indicate which sectors raise up the issues: 1 = waste management, 2 = crowd-sourcing transportation and delivery logistics companies, 3 = a recycling social enterprise, 4 = a producer of recycled material-based products, and 5 = four shopping centres.

As a synthesis, the empirical findings suggest that supply chain management in CE is at an immature stage. In our interviews the business sector identified that there are missing services and actors, needs for deeper cooperation in the value chain and need for totally new ways for collaboration, for example in the form of sharing as well as possibilities to utilize digitalization at all phases of the supply chain, including reverse logistics. Due to altering volumes of waste and recycled material as well as emerging new types of activities, there appears to be a need for new kinds of logistics services. Examples of this are the warehousing needs of reusable waste and delivery services for C2C trade. The high operations and handling costs in different stages of supply chain is now a restricting circular business. Totally new solutions are needed, including new digital solutions, new ways of sharing facilities and equipment and cross-sectional co-operation, or solutions like intelligent mobile warehouses. Consumer's new role was seen as an opportunity, but also as a challenge raise up. The respondents also identified a need to influence the consumers by offering them easy and cost efficient possibilities to participate in circular economy activities.

4.2 Synthesis and What Is Missing in Current Literature

To the best of our knowledge, the academic contribution to SCM in a CE is still very limited, although the importance of SCM is widely recognized. However, two distinct streams of literature, namely SSCM and PSS, offer an interesting basis for investigating supply chain challenges is a CE and should be integrated into the emerging literature of a CE. SSCM/CLSCM appears to give interesting insights into many challenges related to closing the loop, including reducing the high cost of collection and leakage from the system. Several authors [23] have identified useful frameworks to support this. The research on PSSs, in turn, supports the idea of having a distinction between owning and using, and developing business models that enable a shift from ownership to performance-based models. However, publications focusing on the supply chain model for a PSS are still scant, and more research is needed.

Both SSCM and PSSs focus on the manufacturing industry, and the contribution to other sectors and industries is still limited. The changing role of consumers, i.e. becoming users and offering information to the system, and the implications for SCM seem to be almost non-existent in today's literature. The changing role of consumers creates many challenges and requirements for SCM but also possibilities. Companies are able to get more information about consumers and use of the products, which they can apply in the management of the supply chain and collaboration with other stakeholders. Other important approaches to which previous literature has only made a limited contribution relate to cross-sectional (reverse) supply chain collaboration. Moreover, both SSCM and PSSs focus on quite traditional business models, and the supply chain as an enabler for disruptive innovation is an interesting avenue for future research. Table 2 puts together characteristics and challenges of supply chains, based on the managerial/non-academic literature and

Table 2 Characteristics and major challenges of SCM in a CE and research streams that may provide insights

Characteristics	Literature stream
Closing the loop—open or closed loop supply chains, also cross sectional	SSCM/CLSM/Reverse supply chains. However, the literature focuses on the manufacturing sector, and contributions in other contexts are limited
Distinction between using and owning, i.e. business models that promote the use of 'functional service'	PSS. However, the literature focuses on the manufacturing sector, and contributions in other contexts are limited. Contributions to SCM are very limited
The new active role of the consumer, the consumer becoming a user	PSS. However, the literature focuses on the manufacturing sector, and contributions involving consumers are very limited
Transparency throughout the SC	SCM
Challenges	
Lock into today's supply chains, building new supply chains is challenging	Social aspects of SCM, value network (not included in this investigation)
Motivation of different value chain partners to commit to the implementation of business models	Social aspects of SCM, value network, governance models (not included in this investigation)
Co-operation between SC partners, including cross-industry co-operation	SCM, value network
Warehousing, collection and handling	SSCM/CLSCM/reverse supply chain
Distribution on reverse side, especially when involving users	SSCM/CLSCM/reverse supply chain
Balancing the forward and reverse loops and ensures uniform material quality	SSCM/CLSCM/reverse supply chain

empirical data and identifies potential streams of literature that may help in the investigation of these. In addition to the two research streams investigated in this paper, relational aspects of SCM seem to be important to future research.

5 Conclusions

This paper opens up the discussion on SCM aspects in a CE and contributes to the literature by identifying the main characteristics and challenges of SCM in a CE, and by identifying the most promising streams of literature to be applied. We also identify some major avenues of future research. However, as this is only a preliminary study, the topic needs more investigation in the form of empirical research as well as investigating previous research. Other concepts that may be valuable in the investigation of SCM in a CE are Industrial Ecology, Industrial Metabolism and Industrial Symbiosis. These were left out of this investigation as—to the best of our knowledge—the SCM discussion is still limited.

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How Does Sustainability Help or Hinder Innovation?

A Study of Successful Companies Founded on Sustainability Principles

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Abstract This research analysed how sustainability impacts innovation in industry. Qualitative data was collected during interviews with employees from seven companies founded on sustainability principles. The data includes numerous examples of successful and unsuccessful sustainable design and manufacturing initiatives. Research findings indicate that improved packaging, eco-efficiency and the exploration of more sustainable solutions for standard products are fuelled by companies' sustainability principles and successfully drive innovation. Whereas the supply of sustainable materials and trade-offs between sustainability and desirable material properties, as well as costs, represent challenges which can hinder innovation.

1 Background

In 2015 'sustainability' and 'innovativeness' are positive attributes that companies widely want to have associated with themselves as both attributes are considered to have a positive impact on performance and competitiveness of companies that embrace these [5, 11–13]. Sustainability is an important topic to academics and in [9], Lubin and Esty described sustainability as a megatrend with an impact similar to that of globalisation. In the business world, the perception of sustainability as a business slacking cost—as stated by Boron and Murray in [2]—has changed according to Nidumolu et al. [11] and companies widely promote their corporate social responsibility (CSR) efforts in 2015. However, Porter and Kramer in [12] stated that CSR is not seen as an integral component of businesses' strategies. Following the same argument, Marques and Mintzberg [10] criticised that many companies had disconnected CSR from their operations. Porter and Kramer [12] suggested 'creating shared value' as an alternative approach to value creation that

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goes beyond CSR and places societal needs and hence sustainability at the core of the company.

In academia and industry today, sustainability and innovation are generally understood to enhance one another. This general understanding of the relationship between sustainability and innovation represented the starting point of the conducted research. In this study, the following question was examined: '*How does a focus on sustainability help or hinder innovation in successful companies founded on sustainability principles?*'. To answer this, companies that were founded on sustainability principles were selected as the object of the analysis. Therefore, sustainability is inherently embedded in the corporate culture of the analysed companies and will be strongly linked to their sustainable design and manufacturing initiatives and not superficial 'Greenwashing' [4]. Information about successful and failed product innovations was retrieved during interviews with employees of seven different companies.

2 Methodology

This research attempted to provide an understanding of **how** sustainability helps or hinders innovation in business practice. A widely used definition in sustainability is the definition of 'sustainable development' provided by Brundtland [3, p. 8]—it "*meets the needs of the present without compromising the ability of future generations to meet their own needs*". Another approach to sustainability is the triple bottom line framework by Elkington [6] which breaks sustainability down into the environmental, social and economic dimension. This framework suggests that sustainability can only be achieved by acting sustainably in all three of these dimensions. In the business world, different approaches emerged as an answer to the sustainability challenge. Eco-efficiency which aims for a reduced environmental impact, using fewer resources is one example of its application in practice [8]. In contrast, the cradle-to-cradle approach, including the ideas of eco-design, strives for absolute sustainability [1]. In business practice, many companies have implemented eco-efficiency strategies as they lead to direct cost savings whereas few have applied the cradle-to-cradle approach [1]. The second term that needs to be defined is 'innovation'; Tidd and Bessant [14, p. 21] defined "*innovation as the process of turning ideas into reality and capturing value from it*". This definition shows that the scope of innovation goes beyond an idea or invention by itself, it has to be realised, implemented and create value to represent an innovation.

The researched companies were chosen by applying four selection criteria (S1–S4) to ensure their relevance to the research question. The criteria S1 and S3 ensure that the companies are successful, the criterion S2 guarantees that sustainability is at the core of the corporate culture and influences decisions in research and development. Finally, S4 excludes companies where sustainability principles do not

Table 1 Key facts about selected companies

Name	Founded in	Industry	HQ	Employees
A	1995	Clothing	UK	20
B	1986	Toys	China	1600
C	1988	Detergents	US	140
D	1978	Food	UK	70
E	2007	Food	Germany	350
F	1984	Cosmetics	US	400
G	2003	Clothing	Finland	20

affect research or product development, for example as a result of outsourcing these activities.

S1 The company was founded before 2009.
S2 The company was founded on sustainability principles.
S3 The company generates profits today.
S4 The company is conducting in-house Research and/or Product Development.

The chosen companies fulfilled all four selection criteria and operate in various industries based in the USA, Europe and Asia; all these companies are anonymous in this paper (see Table 1 for company details). One employee of each of these seven companies participated in a semi-structured interview. These interviews were recorded and transcripts written, and subsequently thematic analysis was conducted on the collected qualitative data.

3 Results

The results section below presents the findings in two parts: factors which help, and factors which hinder innovation. Within each section, the way in which the factor influences innovation is explored in order to answer the research question.

3.1 How Sustainability Helps Innovation

Improving packaging solutions. Matters related to packaging were mentioned 60 times during the seven interviews and the topic was addressed in some form by all interviewees. This shows the significance of packaging as an 'easy win' for sustainable design and manufacturing initiatives. The interviewees from Company C and Company F both stated that their companies use post-consumer-recycled plastic for their product packaging. The interviewee from Company G also mentioned the use of recycled materials for their packaging and the Product Manager from Company E explained how they reduce packaging material and improve its recyclability. This person stated that they had recently switched suppliers for the packaging of their muesli to-go (one portion of muesli in a small plastic cup) to reduce the amount of plastic by making the plastic walls thinner. Company E also delivers larger quantities of muesli to hotels; these are packaged in biodegradable corn-starch bags.

Reducing waste—Eco-efficiency Wasting material is considered unsustainable and a waste of money. Therefore, many companies try to reduce: material usage for their products and packaging; energy and water consumption; general waste; and transport. Firstly, several of the companies reduce waste during the production process. For example Company B optimises the arrangement of the wood jig for their wood toys to achieve this. The Company B interviewee stated: "*We always see that there are few offcuts, we optimise it so that we use the gaps for small parts and the waste is as little as possible.*" At Company B parts with minor defects are also reworked to further minimise waste. Company G's manufacturing and design follow similar principles but went further with the aim to use all the material rather than minimising waste. The interviewee stated: "*we don't want to waste any material we always try to use everything*". The person went on to explain an example: "*So for example an army laundry sack*[1]*—we want to use every part of it. We might use some part of it to make a bag and then some details like a rope or something we can put into a sweater*". Both companies reduce waste by looking at the materials holistically during the design process of the products and try to minimise waste in advance. They achieve this by optimising the product design and by looking at all their product offerings to find a use for as much of the materials as possible.

Some companies found another way to reduce waste; by thinking about the entire lifecycle of the product. The two companies mentioned above, Company B and Company G, as well as Company A, improve the quality and durability of their products to achieve this. To maximise their products' lifetime Company G repair products for their customers without charge. The interviewee stated: "*we are using a lot of those army materials and they are of such a good quality that they last so long that we even repair them*". Company A even consider the time element in the colour choices for their products. The Company A interviewee said: "*we try to keep colours fairly on trend but slightly behind the curve rather than being the new neon yellow, and then, if you combine that with something that lasts a long time then people should be able to wear it out*".

Company A, Company G and Company E reduce transport by producing and sourcing as locally as possible. For example all of Company G's manufacturing is based in Finland and Estonia. Continuous reduction of energy and water usage of the facilities and the importance of waste management was another recurring theme. The interviewee from Company F stated examples; the company's office and manufacturing buildings are "*zero waste energy*". The interviewee also mentioned that internal waste management is very important and the company has an internal

[1]Their business recycles such items by turning them into products.

waste auditing team to enable recycling. The interviewee from Company D also mentioned waste management and stated that the company has zero waste going to landfill.

Finding more sustainable solutions for standard products During the research, all interviewees provided examples of products that are innovative because they are using renewable and/or natural ingredients that did not cause harm to people and/or the environment. The interviewee from Company C stated his view on the practical implications of sustainability for innovation: "*we have to make products that are familiar to the consumer so in that way we are not innovative. But we have to do it in a way that is much better for the environment that is innovative*".

Company E's employee stated that they exclusively source organic ingredients. The only non-organic ingredient they use is sea salt, as no organic certification exists. The interviewee developed for example a muesli mix with 40 % protein content. It contains organic soy flakes that are locally sourced in Germany. This is significant, as soy is usually imported from outside Europe. Company D use organic and fair-trade ingredients for their products if possible; organic fair-trade allergen free cookies are one example stated where solely organic ingredients are sourced.

Company B offer a line of toys that are made from bamboo which grows very fast and is a renewable material. Another toy line produced is 'Natureline' where different types of wood are used instead of a varnish finish. The company also switched from beech wood to rubber wood blocks for their ball path 'Quadrilla'. The interviewee explained that rubber wood is not only more dimensionally stable at different humidity levels, but he also described the traditional life cycle of rubber wood trees: "*Rubber trees are grown to gather natural rubber but you can only* '*milk*' *them for a certain amount of time and then the trees are chopped and burned.*" Besides finding a raw material with the needed properties, using them for toy blocks instead of burning them retains a higher value of the raw material.

The two U.S. based companies C and F both utilise materials for their detergents and cosmetics that they consider sustainable. Company C not only adhere to laws but set higher internal standards and employ ingredients like bio-based surfactants for detergents that are considered not to be harmful for people and the environment. The interviewee from Company C stated: "*we consider not just regulatory requirements for the environment and human health but [also] how we can make our products as safe for the environment and as safe for people as possible*". The company does not use any chronic toxicants because of its convictions regarding sustainability even though U.S. laws do allow a certain amount of these. Company F also go beyond legal requirements and solely use natural plant- or mineral-based materials and have switched to community sourced raw materials for some of their products. The interviewee mentioned natural anti-aging products as a recent successful product. Company A have an example where the more sustainable material delivers additional benefits to the customer. According to the interviewee normal cotton was replaced by organic cotton for t-shirts and trousers to reduce the carbon footprint (to benefit the environment) and the customers. The interviewee explained: "*If we can use organic cotton not only does it benefit the planet ... but* *also pesticides stick in the fabric and will be taken through your skin and end up god knows where in your body.*"

Upcycling The term 'upcycling' describes the idea of reusing materials to create higher value products. The interviewees from both clothing companies, Company A and Company G, mentioned examples for upcycling. The interviewee from Company A described trousers that are produced from a fabric that is made from recycled plastic bottles. The person said: "*...we created jeans that ages beautifully as others of 100 % cotton fabrics. But we've got 8 plastic bottles per pair of jeans that would have been sat in landfill, that are now being reused in jeans...*" Company G's main design and manufacturing activity is upcycling. It is the smallest company, and is the only 'craft-based' manufacturer of all the companies interviewed. The interviewee described the design of a handbag that is made from seatbelts: "*we have this one bag that is made out of seat belts and then there is this buckle that is an airplane buckle and the lock is the lock of the bag*".

3.2 How Sustainability Hinders Innovation

Issues with supplies of sustainable materials The available sustainable materials represent a constraint to innovation for companies with sustainability focus. All interviewees mentioned problems finding suppliers; e.g. suppliers that hold the necessary certificates or supply needed quantities; whether that is non-harmful or organic ingredients or a sustainable fabric. All interviewees mentioned this but it appeared especially difficult for smaller companies, due to the scarcity of the material or a minimum order size. The interviewee from Company A stated: "*to make a waterproof jacket it is still very hard to find low-impact fabrics for our brand that is still very small*". The interviewee from Company E mentioned similar problems; the company used to produce a squash-capsicum muesli but the minimum order size of these freeze-dried vegetables was too large for Company E to order a second batch. Company E had also been searching for a supplier of organic sugar-free coating yoghurt and the interviewee stated: "*I've been trying to get organic coating yoghurt for years and nobody produces it and because of that I will probably produce it myself*".

Another difficulty Company E face—and that Company B experience as well—is a lack of certified suppliers. Company E's interviewee stated that there are many start-ups that could be interesting suppliers but they are not certified and therefore do not meet the internal requirements. Company F have a similar experience; their natural material policy limits their product range of lip tinting balm (coloration for lips) as some colours cannot be produced naturally. In the 1990s and early 2000s, Company C faced a similar problem when they switched to bio-based surfactants for their detergents. At that time only two suppliers offered bio-based surfactants and they were much more expensive than standard petrol-based surfactants. Now almost all major suppliers offer bio-based surfactants thus reducing the cost of bio-based surfactants. Another example mentioned by the employee from

Company F is that there is a huge range of offerings regarding materials, packaging and suppliers but that internal sustainability requirements limit the options from which one can choose. Striving for sustainability limits choice because many options cannot be considered as they do not meet internal sustainability requirements.

Challenges of sustainable materials from a manufacturing perspective Company G face the challenge of finding sufficient amounts of high-quality used fabric materials and leftovers to allow large-scale cloth manufacturing as they refrain from using new materials. During the interview the employee indicated that "*we still have to be able to control that the quality of the materials is good and that we have big amounts of them because we have to do big production and it is kind of hard to use recycled materials for big production*". Company B also deals with challenges in manufacturing with more sustainable materials; they used a plastic-wood-compound (PWC) for outdoor toys to reduce the use of petrol-based plastic. The interviewee described: "*One problem is that PWC has different properties than pure plastic ... to pure plastic you can, for example add a UV-blocker ... this is not easy with a PWC as the compound is heterogeneous.*" Besides that, the injection procedure of PWC is more complicated as the material has a tendency to form air bubbles on the surface with the standard process. Company B also faced difficulties developing toys from the renewable material bamboo. The process to transform the round raw material bamboo into a raw material for toy parts is complicated but without this transformation, design options are very limited.

Issues with sustainable materials from a customer perspective The research shows that some materials have trade-offs between the sustainability of the used materials and desirable material properties. The case of Company B utilising PWC material which was mentioned above created a problem from the customer's perspective; the bleaching of the PWC as a result of the lack of UV-blockers "*decreases the visual appeal of the product*". Therefore, Company B stopped producing PWC outdoor toys. Company A encountered similar difficulties, the interviewee explained: "*we used to produce a biker hoody with 100 % Merino wool and it was a great piece but it was very sensitive to pilling and it would pill literally in the first week so you've been looking at a 25/30 % returns rate on it*". Company A also produced 100 % organic cotton sweatshirts in the past "*but after the first wash it was like wearing a sweatshirt made of plasterboard or plywood*" which resulted in many customers returning the product. The company managed to solve these problems by adding acrylic to the Merino wool and polyester to the organic cotton. The interviewee explained that it "*washes much better, it lasts longer, it has a much nicer hand feel*". Company A and Company B both pointed out that the respective modifications came at a cost of reducing the recyclability of the products. Company G had a different challenge, when the company was founded the concept of making new products out of 'old' materials was perceived by customers as a sign of the products being low-quality. Over the years, the company has established a customer base that recognises the quality of the products, and today upcycling is a trend from which they benefit commercially.

Company F also face issues when it comes to customer experience. The texture of their natural-based sunscreens is pastier and does not spread as well as those of their competitors, who employ synthetic ingredients in their products. Thus, Company F cannot achieve "*the exact same efficacy*" and "lay-down" (how cream spreads and is absorbed by skin) compared to other products. The interviewee said that in some cases customers accept trade-offs in favour of the known sustainability benefits of products.

The cost factor The cost factor is summed up by Company F's employee "*It is a hard balance to be profitable and have a good margin on the products that you deliver against the natural and sustainability which you obviously consider important.*" Other interviewees confirmed this statement. For example, Company G created shoes that consisted of a bottom and a top part that could be attached with a zipper. People could buy different shoe tops and attach them to the sole. "*So you had one bottom part and many different shoes.*" These shoes had to be marketed at a price of approximately €200 which was less than the manufacturing and logistics costs but more than most customers were willing to pay, ultimately resulting in a failed product. Another example is the aforementioned case of Company B's bamboo toys that also has a cost dimension to it; many customers are not willing to pay the higher price, which results from the complicated transformation process of the raw material. The interviewee from Company A also mentioned that there were cases "*where products have died purely because they just can't be made within a reasonable retail price*".

A matter of convenience for customers Company C launched concentrated detergents in the past to decrease the packaging and transport impacts but customer demand for these products was low. Prior to using these concentrated detergents, customers had to fill them into a bigger bottle and top them up with water. "*Consumers don't like the extra step of having to add water*" was the interviewee's explanation; the product failed and was taken off the market. A second example where customer convenience was an issue are the two part shoes from Company G. The interviewee remarked that low sales of these shoes might not have been solely down to the high price but that the extra effort for customers to unzip the sole and zip it to a different top when wanting to wear different pair of shoes might also have played a role in the failure of this product in the market.

4 Discussion: Practical Implications of the Findings

4.1 Taking the Initiative

The supply of sustainable materials, the properties of these materials, their cost or the processing of the materials in manufacturing represent examples of challenges that several companies experienced. The research shows that striving for sustainability required creativity and out-of-the-box thinking to solve these problems.

Company B has established a bamboo research centre to develop the use of the material further and supported bamboo suppliers with achieving the necessary certification. Company E has considered producing organic sugar-free coating yoghurt themselves as no suitable supplier was found.

4.2 Long-Term Orientation

Two interviewees stated that their companies launched products knowing they would make a loss (Companies A and G) or ones that would have a low profit margin (Company F). The aim was to establish the products in the market and reduce the cost later. A successful example is the use of bio-based surfactants instead of petrol-based ones by Company C, despite the initial significantly higher price. In the case of Company C, over time, more suppliers offered bio-based surfactants and the price of bio-based surfactants has gone down. These examples show that long-term thinking rather than orientation towards short-term profits has helped to improve the sustainability of their design and manufacturing initiatives. This finding corresponds with the long-term orientation of Brundtland's [3] definition of sustainable development.

4.3 Sustainability as an Opportunity

As Nidumolu et al. [11] stated "*that smart companies now treat sustainability as innovation's new frontier*". By this Nidumolu et al. [11] did not refer to sustainability as a fixed frontier but as a boundary that can be pushed by innovating. The research reported here has shown how sustainability can both drive and hinder innovation. Other companies can take these findings and find ways to push the boundary or overcome difficulties in their own industries. The examples from the analysed cases show that companies can innovate by making traditional and established products in a more sustainable way by e.g. changing the design, considering its lifecycle and changing the materials or the production processes. These steps represent only two of four options from the innovation typology of Tidd and Bessant [14], namely 'incremental performance and quality improvements of existing products and services' and 'development of alternative technologies in existing applications' therefore the steps 'creation of novel product and service niches' and 'co-evolution of new socio-technical systems' may still offer significant potential for new sustainable service, design and manufacturing initiatives in these companies. The cases reported here show that grasping sustainability as an opportunity does help companies to focus their R&D efforts and can be an inspiration for innovation.

4.4 Limitations of This Research

The topic of how sustainability principles help and hinder innovation was explored in seven companies worldwide that vary in size and industry. The research demonstrated that despite all analysed companies having been founded on sustainability principles, they all have different sustainable design and manufacturing initiatives. What these companies have in common is striving for sustainability and continuously working towards this goal. These diverse companies experienced many similar problems. Therefore, the findings are not specific to one industry or country and thus may be applicable to other companies.

However, in order to confirm these generalisations, further research is needed. A larger sample of diverse companies is necessary that may include companies that were not founded on sustainability principles to ensure that research findings are relevant for those as well. The validity of the results could also be improved further by collecting other sources of data, such as company documentation and sales figures. The additional data would allow determining which other factors impact the success and failure of products and companies' innovativeness.

5 Conclusion

The aim of this study was to explore how companies' sustainability helps and hinders innovation. To achieve this, interviews with employees from seven companies founded on sustainability principles were conducted. This research shows that sustainability principles may not only drive innovation but may also provide some barriers. The main hindrances for innovation represent the supply of sustainable materials, challenging material properties and the consequences of these properties for customers and manufacturing. It was also revealed that sustainability helps innovation by rethinking packaging, establishing eco-efficiency and delivering more sustainable versions of existing products. Practice examples illustrated that long-term thinking and creative problem-solving represent ways of overcoming these hindrances in some of the cases. Further research should look at sustainable design and manufacturing initiatives in a larger sample and include other documents as part of the data collection.

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A New Sustainable Product Development Model in Apparel Based on 3D Technologies for Virtual Proper Fit

Evridiki Papahristou and Nikolaos Bilalis

Abstract As awareness on fashion's impact on our world is growing, there are key leaders in the industry who are beginning to question the impacts of the model built on careless production and endless consumption. 3D Virtual Prototype, 3D visualization, 3D Body Scanning and virtual try-on technology solving the proper-fit problem, while providing efficiency in its supply chain, can help the clothing sector meet green targets, without damaging the environment through wasteful manufacturing processes. Concepts of CSR and Collective actions on Sustainability are being explored within the apparel sector. Authors examine the challenges, the threats and the opportunities across the supply chain partners emerging to reduce the environmental footprint. A new fully integrated product development model is proposed, with 3D virtual simulation of design concepts on mannequins that represent the target market of the company with digital fit models based on accurate input size data.

Keywords CSR · Sustainable product development · 3D virtual try-on · Garment fitting · Proper-fit

1 Introduction

As awareness on fashion's impact on our world is growing, there are key leaders in the industry who are beginning to question the impacts of the model built on careless production and endless consumption. The pace of innovation in technologies (applied to the product development phase) is reaching the stage where it can keep up with consumer demand in markets like these. 3D Virtual Prototype, 3D visualization, 3D Body Scanning and virtual try-on technology solving the

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proper-fit problem, while providing efficiency in its supply chain, can help the clothing sector meet green targets, without damaging the environment through wasteful manufacturing processes.

One of the biggest problems fast fashion companies face is the constant challenge of productive relationships between internal departments (separated by silo mentality), processes, solutions, as well as those between external suppliers, their processes and technology solutions [1]. CSR regulatory compliance and operational effectiveness add to the previous challenges and apparel corporations require to take action. New digital solutions are supporting PLM and CSR programs operating across the entire end-to-end Supply-Chain addressing to the needs today's complex apparel sector.

The purpose of this paper is to document first, the concepts of CSR and Collective actions on Sustainability. It is argued that most of the sustainability issues should be addressed during the design stage.

Through our research a number of research questions were investigated such as: Why has the industry's view of sustainability been difficult to monetise, even if the new model of fast and furious fashion is more complex with higher environmental impact? What are the challenges need to be addressed in order to manage emerged issues like the reduction in the use of intermediaries between producers and retailers as means of further eliminating cost? Why are these issues threatening retailers on operational effectiveness? In what way does the fashion industry approach the social and environmental challenges emerging from the supply chain? Can new technology solutions like PLM (Product Lifecycle Management), 3D visualisation or 3D prototyping work with and across supply-chain partners to reduce the environmental footprint of their processes? Can fit problem solving, extend the useful life of clothes and reduce the environmental impact of clothing in use through design and services?

The final intention of the research is to present a new apparel product development model, encompassing various digital tools which aim at addressing the above research questions.

1.1 CSR (Corporate Social Responsibility)

The globalised production of textile and fashion goods has made it more difficult to regulate standards with regard to environmental impacts through a "single country policy". The development of CSR programs in development countries has occurred in response to increasing consumer interest in social and environmental impacts of business activities wherever they operate in the world.

Corporate Social Responsibility (CSR) refers to actions or business practice that companies taking responsibility for ethical and environmental concerns. Usually, it's a banner under which small businesses and multinational corporations alike have emblazoned on marketing materials online and in-store [2]. Ideally, well-managed CSR creates social and environmental value, while supporting a company's business

Fig. 1 CSR benefits

objectives and reducing operating costs, and enhancing relationships with key stakeholders and customers [3].

Although it provides numerous benefits like Fig. 1 is showing, the fashion industry have just recently realized its importance and significance.

1.2 Collective Action on Sustainability

The more immediate challenge in CSR remains the management of public perception and the avoidance of negative association between the parent brand and ongoing ethical and environmental crises [2]. World's leading fashion brands within the Sustainable Apparel Coalition (SAC) share the same vision as stated on SAC's website: "*The Coalition's vision is an apparel and footwear industry that produces no unnecessary environmental harm and has a positive impact on the people and communities associated with its activities*" [4].

The Higg Index[1] (the core driver of SAC) delivers a holistic overview of the sustainability performance of a product or company.

WRAP,[2] a UK resource efficiency experts organization, influences the design of everyday items, such as textiles, and is helping to transform how we buy, use and dispose of these goods, especially clothing. In 2013 the SCAP[3] 2020 was launched

[1]The Higg Index (launched for the first time in 2012), is a suite of tools designed to allow fashion users—from factor managers to designers and sourcing teams—to drive meaningful change in their methods, and to minimize their negative impact on workers and ecosystems worldwide.

[2]WRAP: Waste Resource Action Program.

[3]SCAP: Sustainable Clothing Action Plan.

Table 1 SCAP 2020

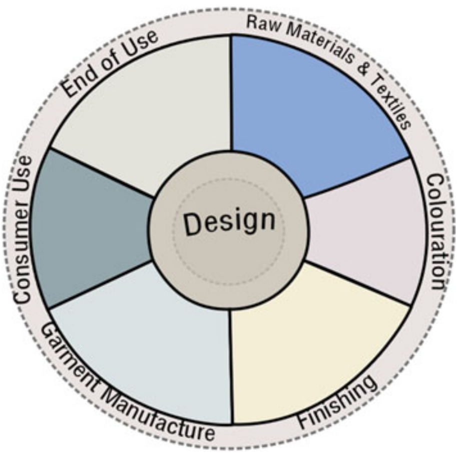
SCAP 2020 Commitment—the seven action areas	
1	Use a common assessment tool to measure our baseline position and track changes in footprint over time
2	Reduce the environmental footprint of clothing through fibre and fabric selection
3	Over the longer term, work with our supply chain partners to reduce the environmental footprint of their processes
4	Extend the useful life of clothes and reduce the environmental impact of clothing in use through our product design and services
5	Develop effective messaging to influence key consumer behaviours which will reduce the environmental footprint of clothing
6	Increase re-use and recycling to recover maximum value from used clothing
7	Develop actions that help keep clothes out of landfill

when WRAP identified key action areas that could deliver the biggest reductions in the environmental impact on clothing. The signatories represent 40 % of the whole UK clothing market including Tesco, M&S, Nest and fashion designer Stella McCartney [5]. The seven action areas of the commitment are as it is shown in the following Table 1.

Another initiative is Sustainable Fashion Academy [6], the world's first on-line course. It has been launched as a new tool relevant for companies looking for flexible and cost-effective and training in sustainable apparel. Divided in six modules, where the fourth one is focused on how the product design can offer sustainable solutions, equips designers and entrepreneurs at the product development level, with the knowledge and tools they need to develop and drive apparel innovations and at the same time contribute to improve a company's sustainability performance.

Figure 2 are the most important stages during a garment's creation and use. Design is put in the middle because decisions that are made during the design phase

Fig. 2 Important stages



can influence performance during all the other stages. Moreover, the stages are put into a circle surrounding design, because the process of making and using a fashion product does not have to end when a customer has finished with it. The material can have many lives; can be re-used or re-cycled to create new fashion products.

2 Understanding the Evolution of the Sector—More Focus on Design and Digital Solutions

Today the fashion collections may be smaller, but there are more of them. Instead of having four seasons and four collections a year, the industry now has fifty two with new products coming in stores every week. Fast Fashion has become faster and more furious. This means more size, colors, and variations to manage. If we multiply that by the many geographic versions where the company is present, the complexity increases further. As fast fashion accelerates, and shoppers require their needs to be met at the right price and on the right day, retailers need to work harder to ensure ethical compliance in their supply chains [7]. On the other hand, consumer is relenting in his demands and increasingly sophisticated; high quality, low prices and constant newness are what interest him today. The market is increasingly saturated and combined with the above, makes tried and true fashion strategies such as geographic expansion and internationalization more complex than in the past [8].[4]

Digital prototype in the textile and clothing industry enables technologies in the process of product development where various operators are involved in the different stages, with various skills and competencies, and different necessity of formalizing and defining in a deterministic way the result of their activities. Taking into account the recent trends in the industry, the product development cycle and the use of new digital technologies cannot be restricted in the "typical cycle" but additional tools and skills are required to be integrated taking into account these developments [10].

2.1 Development of New Digital Tools and Solutions

As a result, big corporations focus at the beginning of the process, where the product is designed and developed. Usually, most manufacturers begin the design phase in the traditional manner with 2D sketches and concept production. This creative output then passes through the classical product development cycle, from preparation of the cut pattern and modifications, to sewing prototypes, and after innumerable iterations with many samples traveling back and forth between the

[4]Patagonia, prefers the word customers instead of consumers; prefers customers who recognize the impact of their consumption [9].

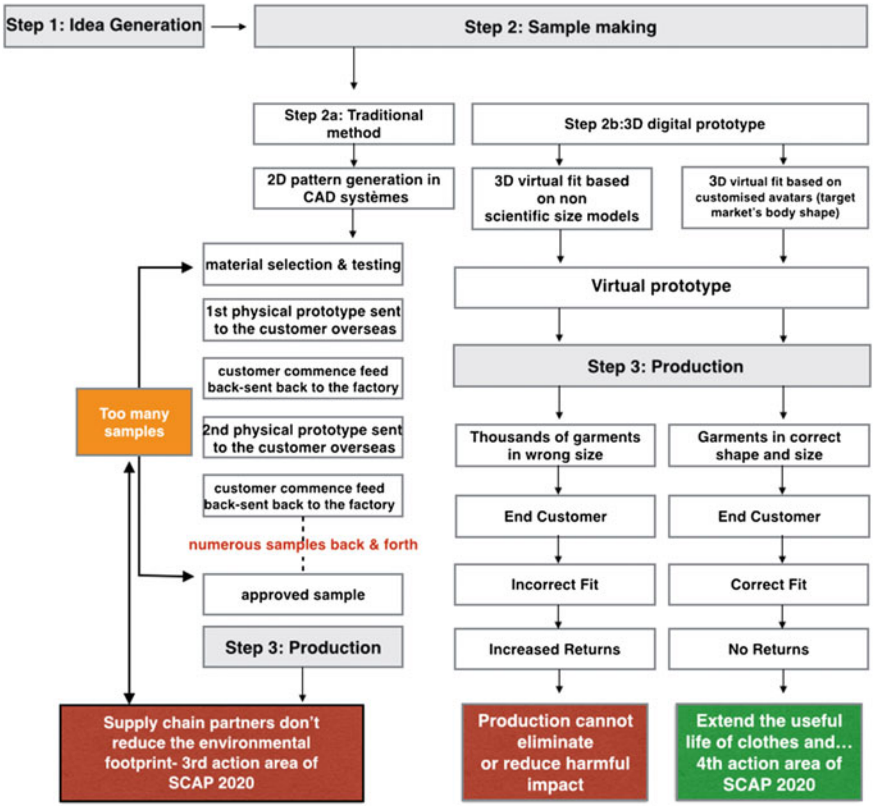


Fig. 3 Sustainable apparel design and production model

factory and the customer, finally reaches the production stage (Fig. 3). In a fast and furious industry like the one of apparel, this process does not seem to work anymore. The previously mentioned product development process is a cycle which is related to a large group of people; creative teams and technical designers who need to work seamlessly regardless of location. Designers, pattern makers, product development team and manufacturers need to visualize the same and make sure that everyone understands the type of modification need to be done.

The *design process* needs improvement so that sustainable design is not an afterthought, but is incorporated centrally throughout the design process from its outset.

In the sampling process with 3D virtualization tools and solutions, fashion companies are helped to optimize their workflow. Colour visualization, design details and print placement can be decided quickly and early-on in the process, reducing Design Lifecycle and more importantly number of samples. Vendors like Browzwear, Clo3D, GerberTechnology, Human Solutions, Lectra, and Optitex, provide such tools. Not only they allow designers to test new ideas for visual accuracy and visualize effects immediately, they can even make pattern corrections interactively and iterate virtually early in the process.

Therefore 3D virtual product development and PLM innovations can create a change in the sector reducing environmental impact and promote social equity. This ensures that the lead-time in getting the prototype right is reduced and gives a customized final sample which is more sustainable. Indeed, these tools are not only making fashion better, faster and more profitable but they fall right in line with companies' increasing desire for green practices: fewer prototypes mean less energy spent on shipping and transportation, less water and fewer chemicals used in preparing fabrics for samples before even creating and reduced waste. Some of the benefits the 3D digital product offers to the product development is less samples, faster prototypes, much higher quality earlier-on in the cycle, and the ability to make decisions based off of that [11].

Results/Drive sustainability:
No more paper pattern tests
For some styles, no physical samples
Over 50 % faster

Some vendors even talk about cutting the overall product development time by 30–50 % [12]. Indeed companies like F&F[5] after implementing 3D virtual prototyping technology in the design development process, have reduced the number of samples made for each product to 1, 2 comparing to 1, 8 18 months ago [13]. Target's goal is to reduce samples by 65 % [14]. Designers and users on the other hand of this new 3D Design tool state that it's a much complex thing, because a garment from patterns on to a 3D avatar needs more time than what most people think. Quite so, sustainable design implementation methods (like 3D virtual environment) within a company's development process, particularly in the case of complex organizations and products, need further improvement. In the case of apparel it all comes down to draping and proper fit, thus a significant development in avatar realism is needed.

2.2 The Problem of Fit-Challenges

Achieving well-fitting garments matters to consumers and, therefore, to product development teams, garment manufacturers and fashion retailers when creating clothing that fits and functions both for individuals and for a retailer's target populations. New tools and software for body scanning and product development

[5]Clothing branch of UK supermarket chain Tesco.

enhance the ways that sizing and fitting can be addressed; they provide improved methods for classifying and analyzing the human body and new ways of garment prototyping through virtual product development [15].

Fashion customers have been convinced to buy clothes online but it's been difficult to convince them to keep them: up to 1-in-4 garments online are returned [16] and 50 % of returns are due to poor fit [13].

This is mostly due to the wide variations in size ranges between different geographic markets. For example, a fast fashion retailer selling the same size garments in Japan, Germany, Finland and Portugal. The body shape and size of customers from these markets is completely different, but the retailer expects the garments to fit all.

Experts agree that new technology innovations like the 3D prototyping can reduce numerous samples but point out that the truth is in the context. Shipping of prototype back and forth, back and forth many times obviously happens a lot because of traditional prototyping process. The truth is though that we are talking about just few garments being produced which are just waste. If you ship back and forth one prototype and get it fit perfectly for the target market (obviously 3D prototyping is even better) but getting the prototype right even if it encores some waste, is more important than ending up with a prototype that does not fit the target market; instead you end up producing too much XXL size i.e. for the Portuguese market.

3 Development of Programs and Solutions to Support Fit and Sustainability

Recent technological developments place a growing demand on product development teams to reconsider their approach to prototyping, sizing and fitting. Significant, related changes are also being made in the fashion retail environment, including innovations in virtual fit to enable consumers to engage with fit online [15].

Examples of these innovations are Virtusize[6] solution which lets customers compare specific measurements of an item they are looking to buy with a similar item they already own. Asos, Oasis and Stylebop are some of the online retailers using virtual fitting solutions like Virtusize to help reduce returns. Clothes Horse, TrueFit recommend size based on what the consumer wears in other brands. Fits.me has integrated even more this virtual sizing technology into the e-commerce shopping journey. It changed its robotic mannequin forms into human avatars, has increased customer engagement from 40 to 70 %, and had a significant impact on reducing returns. Reducing returns means extending the life cycle of clothes; means

[6]https://www.virtusize.com, solution for helping customers choose the right size and fit.

less clothes out of landfill; means two out of seven action areas of SCAC 2020 Commitment are being met (Table 1).[7]

All the above solutions are being developed at the back-end of the supply clothing chain. Gill [15] argues that for best effect in the short term, such advances need to relate well to existing manufacturing practices and to the methods that have, over many years, become embedded by practitioners into the processes involved in clothing product development and those used for establishing garment fit.

- Validate fit throughout the size range early-on
- Decide which sizes to produce
- Guarantee design integrity for each size

The authors of this paper strongly agree and propose a more sustainable product development model based on two different applications of the 3D visualisation technology in the apparel industry: (a) the virtual try-on technology which mimics a customer’s dimensions and displays what a certain garment might look like when worn, offering fit guidance solutions and (b) virtual prototyping technology which tries to alter the way physical apparel prototypes are being made, making adjustments across complete size sets and reducing the need for numerous paper patterns, fit-checking and samples in the development stages. A model that integrates the 3D technology applied so far separately in e-tail of a finished product and in the design/development of a fashion prototype accordingly, enhancing the connectivity of all those involved from the on-line shopper to the producer.

The right technology can help brands and retailers to unlock new levels of transparency, and collaborations between sustainability organizations and PLM and extended PLM developers can drive these opportunities further.

Most vendors strongly argue that collaboration is a key word in technology. All the needed information and data is there. It is just that they are not shared. Today everyone is collaborating. Effective collaboration [17] between: (a) companies which look at size analysis of target market, consumer shapes and sizes and produce size ranges and size studies based on fit preferences and (b) software providers of PLM systems and 3D virtual solutions for the whole supply chain is the key to a new business practice that:

- Improves the process by replacing unnecessary rounds of prototyping by quick and interactive virtual iterations,
- Creates a stable, transparent, sustainable and mutually beneficial channel between end-customers and clothing producers.

[7]http://fits.me/try-it-now/ a Rakuten Group company, enables leading apparel brands, retailers and merchants to engage with their shoppers, personalize their purchase journey and enjoy valuable operational insight through a portfolio of solutions centered on Fits.me’s expertise in fit preferences.

4 Conclusion

A strategy and roadmap is needed for the clothing sector to work towards sustainable vision that is commensurate with try scale of footprint challenge. The authors of this paper believe that if you can use 3D in the concept creation phase then the product development stage will increase significantly. Since different people are involved in the end-to-end development process, it's not a horizontal line; it is a loop. The earlier the designer can come with a concept, the earlier the birth of a concept can be visualized, the faster the people can make decisions on the style, design, colors, fabric, price, fit. The earlier you can have all this resolved, the better the decision can be taken; the more times you can have ideas evolved the faster you can do it. The next most important to a fast, accurate, transparent decision is one that fits properly and it is not returned. In conclusion, fully integrated digital solutions with 3D virtual simulation of design concepts on mannequins that represent the target market of the company with digital fit models based on accurate input size data and not on body measurements that took place decades ago. As McCann [18] very well describes it, the opportunity (the development of sustainable functionality) is beginning to present itself and the software company which develops the tools first and the brand who uses them to repair potential rifts in the fabric of their international operations, may well be favored.

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Part II
General Track 2: Sustainable Manufacturing Processes and Technologies

Generic Approach to Sustainability Improvements in Manufacturing Ovens

Frederick Pask, Peter Lake, Aidong Yang, Hella Tokos and Jhuma Sadhukhan

Abstract Improving industrial ovens is an important objective for sustainable manufacturing due to their significant energy consumption and impact on final product quality. A generic approach for sustainable oven development is presented that focuses on reducing the environmental impact of the oven and manufacturing superior product. The approach focuses on developing product understanding, process improvement and process parameter optimisation. An application example for an oven is presented, in which understanding of cure was developed to highlight how temperature variation affects product quality. This led onto process improvements that developed temperature uniformity and system responsiveness by lowering the thermal mass of the oven structure; resulting in 89 % reduction in heating and cooling times respectively, saving 202 h of annual downtime. Process parameter optimisation was applied and saves 25 % of natural gas consumption per year. The approach is flexible and can be replicated throughout the manufacturing industry.

Keywords Industrial oven · Sustainability · Optimisation · Energy saving · Product variation

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1 Introduction

Industrial ovens are commonly found throughout the manufacturing industry and are used for curing, drying, or baking. They are used for continuous or batch operations, with energy being supplied directly or indirectly. An oven's performance, compared to the best available practice, decreases over time due to structural/mechanical degradation, technology advancements or changing process requirements. There is potential for sustainability improvement in many existing industrial ovens.

Heating applications consume almost 1/5 of all industrial energy [1], and as ovens are an important heating process they have a substantial energy footprint. Energy saving within heating processes is relatively common throughout literature [2, 3]. However, research mainly focuses on minimising energy across an entire manufacturing process, rather than within a unit. Although very beneficial, site wide process improvement is often unfeasible due to limitations in existing technologies, space availability, layout restrictions, heat losses, disruption on production, financial viability, etc. Reducing energy consumption of oven units offers a focused and feasible approach to energy saving. But consideration of how it affects efficiency of the other assets in the factory is needed.

Creating a sustainable oven system considers social, environmental and economic factors. Increasing efficiency and decreasing waste has a positive effect on the environment while improving the oven's capability to manufacture quality product has economic impacts. Process variation impacts product quality and should be reduced. Inconsistent processes impact on performance, cost, safety of a product and efficiency. Safety of workers being a key social impact of oven operation. Understanding process variation has many benefits, and is critical for a manufacturer to be competitive. It can be used to develop better products, avoid excess precision, minimise defects, allow for faster transition between products, deliver cost reduction and to reduce scrap [4]. Tools such as Total Quality Management, and specifically Six Sigma, are used to highlight areas of an oven process which need improving, but can also establish modification plans [4]. The same principals have been applied to reduce energy within industrial ovens by 29 % [5]. Research has highlighted the important link between product quality and energy reduction [6].

Throughout literature, there is a lack of focus on improving industrial oven performance from a holistic viewpoint, as well as industrial operability analysis and clear improvement techniques which can be applied in practice [7]. This paper presents a general management approach for industrial ovens that aims to increase the oven's sustainability. By following the approach it is more likely to achieve energy saving, process variation reduction and product quality enhancement. The paper is structured by presenting a methodology for holistic oven improvement, followed by a description of each stage. An application example is presented to demonstrate the intended use.

2 Methodology

A generic approach to improving industrial ovens includes three stages:

1. Product understanding
2. Process improvement
3. Process parameter optimisation

Each stage of the approach should be completed in order and highlights the importance of product understanding for enabling oven improvement projects. The order of activities is important for correct decisions to be made at the correct time, allowing for maximum benefit.

2.1 Product Understanding

Product understanding provides insight into what is required from the process to deliver a product which performs to specification. It aims to understand what affects product quality, which can be the determining factor for many modification projects. This work acts as an enabler to determine the viability of future projects, by understanding risks associated with projects or by quantifying potential quality improvements. It is important to establish this knowledge at the beginning of the improvement approach, because it will enable the right decisions to be made quickly.

2.2 Process Improvement

Process improvement develops operability and oven capability under current process settings. Analysis of the system evaluates how close to its original specification the current process performs, which can identify areas of process improvement. This can then be developed to exceed and enhance the oven's original capability. Improvements are likely to be physical changes to the oven system e.g. upgrading equipment or installing additional hardware. Reducing process variation, increasing operability, controllability and energy efficiency are all important aims of this stage. Process settings are set based on product understanding. Therefore, the development of product understanding can identify process constraints and potential process improvements.

2.3 Process Parameter Optimisation

Process parameter optimisation is the final step of this approach. The optimisation procedure questions whether the existing process settings can be altered in order to give benefits to process variability, product quality as well as energy consumption. Optimisation involves detailed analysis of process variables through empirical or theoretical approaches. Energy reduction is a key target in this stage, with the optimisation of process variables often being cost effective. This is the final stage because optimisation of a process should only be completed once satisfied with the physical set up of the system.

3 Case Study: Industrial Oven Improvement

In order to demonstrate the intended use, the approach has been applied to a festoon oven that cures adhesive resin to a backing film. Energy is supplied to the oven with direct fired gas burners with fumes exhausted to atmosphere. The oven performs its task reliably, however it was identified as an area of improvement and energy saving because a significant proportion of the site's gas consumption is consumed within it, and it is the first oven in the process line, thus significantly impacting on cure.

3.1 Process Specific Flowchart

Figure 1 presents a flowchart which interprets the high level generic approach for this specific manufacturing application. It shows the specific steps taken through this oven improvement project.

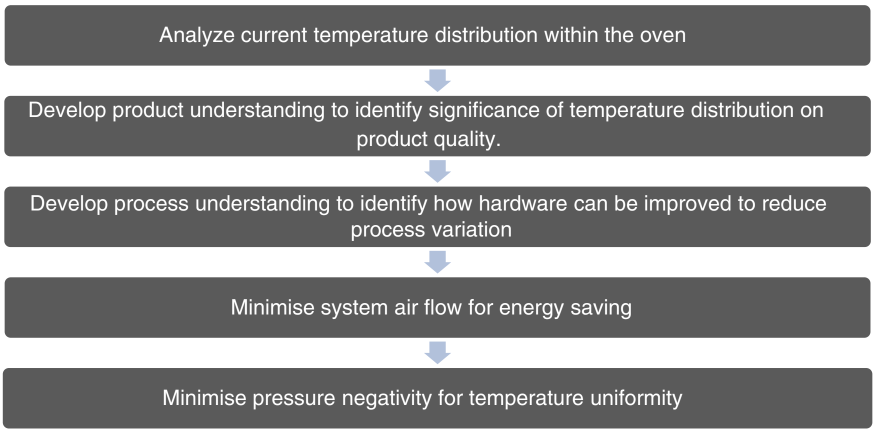

Fig. 1 Process specific flowchart

3.2 Product Understanding

A gap in product understanding was knowledge of how temperature variation affects adhesive resin curing. The webbed product is in repeating loops as it moves through the oven. Temperature profiling was conducted to understand existing variation. Probes were attached to the web as it moved through the process. Figure 2 shows the average cross web temperature deviation for one product above and below its set point. As well the average temperature variation, the analysis also determined that there was greater variation at the start and end of the process than during the middle stages.

Knowledge of cure was required to understand the impacts of temperature variation on product quality. The cure of a resin is represented on a scale of 0-1, and is a measure of the relative number of cross links which are formed with respect to complete vitrification of a thermosetting adhesive [8]. Understanding cure can help identify the most appropriate process strategies. In this particular case, it was not known what level of cure was being achieved in the process, or the level of cure that should be targeted. The resin was analysed using Differential Scanning Calorimetry (DSC); an established technique for the modelling of curing kinetics of epoxy based resin formulations. The Arrhenius nth order equation is one of the most common kinetic curing equations; shown in Eq. (1).

$$\frac{d\alpha}{dt} = Z\,\mathrm{e}^{\left(\frac{-Ea}{RT}\right)}(1-\alpha)^{n} \tag{1}$$

where α is the conversion of cure, t is the time, Z is the reaction constant, Ea the activation energy, R the gas constant, T is the absolute temperature, and n is the order of reaction. Equation 1 is used for data fitting and regression, and is deemed to be generic for modelling cure kinetics [9]. Figure 3 displays the exothermic

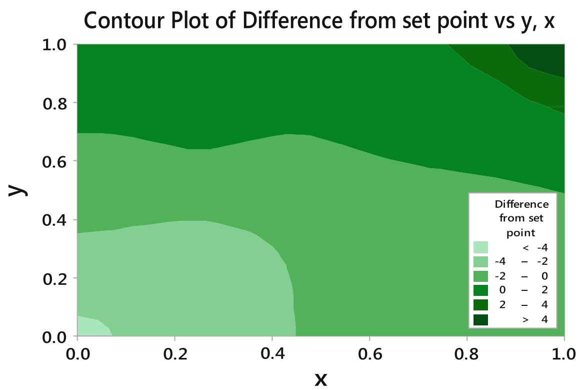

Fig. 2 Vertical web temperature profiling

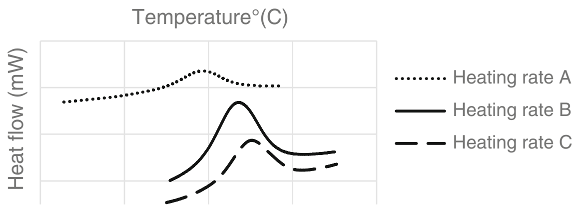

Fig. 3 DSC plot of exothermic regions for different heating rates

region of heat flow from DSC plots for different heating rates, which determines parameters for the Arrhenius nth order kinetic model (numerical values have been removed due to confidentiality). The total enthalpy of the curing reactions (area under the curve) for each heating rate would be the same if the reactions were identical. Figure 3 shows this is not the case highlights how heating rate variation results in different final cure levels; important for product quality.

Alternative kinetic curing models were considered [10–12], but given the complex nature of the adhesive formulation being analysed, it was determined that Arrhenius is the most robust model, and provides sufficient information for this study. As the heating rates A, B and C represent a feasible variation in the oven, this study has demonstrated process temperature variation can significantly affect product cured when exiting the oven, and thus significantly impacting quality. This indicates that consistent heating rates decrease quality variation (e.g. product life), which has important economic and environmental benefits due to reduced waste and customer satisfaction. Product understanding highlights an aspect of the process that needs improving and can be used as justification for process modifications.

3.3 Process Improvement

Process improvement aims to improve system controllability, process variation and energy consumption. Product understanding highlighted the importance of delivering a uniform temperature profile which includes vertical temperature variation and system responsiveness to temperature change. Products are run sequentially (there maybe 8 product changes per week) and discrete run sections can be exposed to different temperature profiles (hottest profile 50 % higher than the coolest). Structural thermal mass limits the oven's ability to change temperature resulting in long start up periods, unnecessary downtime during breakdowns. The existing wall structure consisted of thermal blockwork, insulated cavity, and an external block skin. A modification to install a 50 mm insulation layer to the inside of the oven wall is being proposed. Insulation to the inside oven wall will develop a uniform temperature profile. The aim is that this will improve the environmental and economic performance of the oven due to energy saving in heat loss and unnecessarily long downtime and also improve product quality.

A model was used to calculate the conductive heat flow through the wall structure using the common heat transfer equation shown in Eq. (2); where ρ_α is the density, C_p is the specific heat capacity, T is the temperature, t is the time, k is the thermal conductivity, and x is the layer thickness. The boundary conditions assumed a constant internal oven temperature, and a constant external ambient air temperature. For heating, the initial condition was an ambient oven wall temperature. Numerical solutions were obtained by discretising the model with a time interval of 1 s, and a layer thickness of 5 mm. Once a steady state temperature profile was reached, this profile was taken as the initial condition to model the cooling effect. For cooling, burners are turned off and the fans replace warm air with ambient air. Ambiant temperature external air was the boundary condition.

$$\rho C_p \frac{dT}{dt} = k \frac{d^2T}{dx^2} \tag{2}$$

Figure 4 displays the output from the model for the wall cooling temperature profiles with and without a 50 mm insulation facing (numerical values have been removed due to confidentiality). The model output reduces heat up is reduced by 9 h (90 % reduction), and as shown in Fig. 4 the cooling time for the inner wall temperature to a safe temperature is reduced by 3 h 30 min (88 % reduction). These reductions will save an estimated 202 h of downtime per year. Furthermore, the energy held within the fabric of the structure will also be reduced by 64 %. This work benefits operation, productivity and deliver a consistent thermal regime to the product, ensuring uniform product quality. Process improvement has increased system capability which positively impacts on economic and environmental aspects

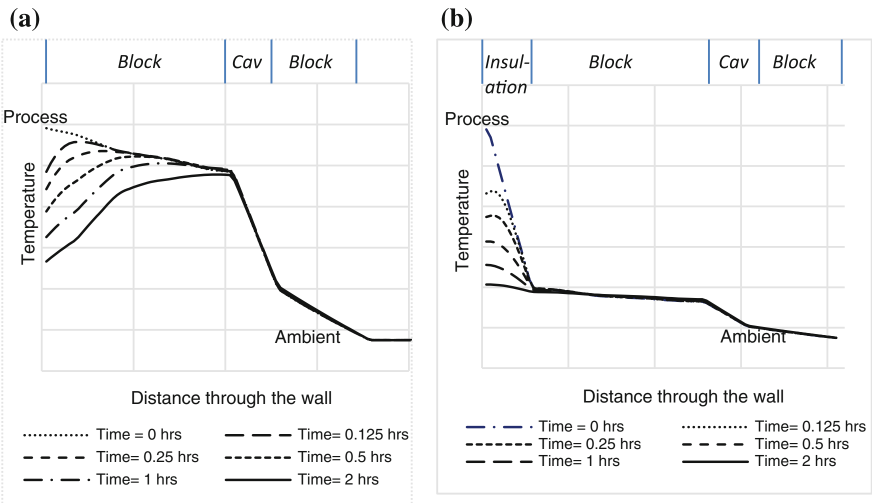

Fig. 4 Heat transfer model output for cooling through the wall structure, **a** cooling of existing blockwork, **b** cooling of insulation faced blockwork

of an oven. Process improvement builds on knowledge gained from product understanding to identify areas of the process which can be improved. In this industrial case study, installing insulation to the inside of the oven wall will help increase productivity, save energy and assist in the development of a uniform and consistent temperature profile.

3.4 Process Parameter Optimisation

The final stage of the holistic approach is process parameter optimisation. The aim is to identify optimal settings that reduce energy consumption while also helping to create a uniform temperature profile. Pask et al. [5] outlined an optimisation methodology for industrial ovens which was used for process parameter optimisation. This systematic approach follows the Six Sigma principles and applies them for an oven scenario. Figure 5 displays the system under consideration; showing a direct fired gas burner/heater box, three fans (F), five dampers (D), and the ducting and recirculation system. The dashed line passing through the oven represents the web path. Baseline air studies found that the system exhaust flow was 16 kg/s, it was decided that process capability would allow for this to be reduced and still

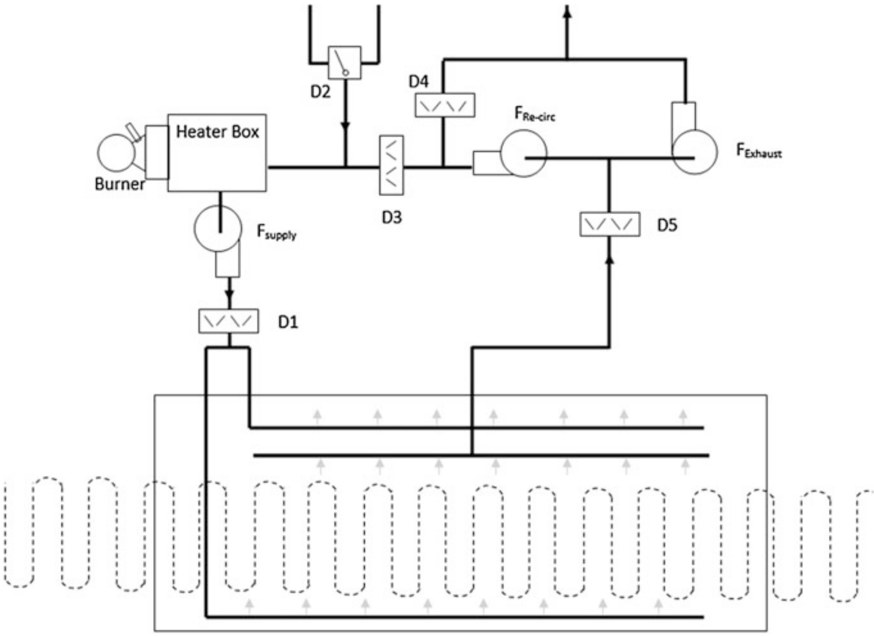

Fig. 5 Oven system under considering; showing fans (*F*), dampers (*D*), ducting, and the oven chamber with web path (*dashed line*)

Table 1 Optimised settings for three process fans

Fan	Existing setting %	Optimised setting %
Supply	100	100
Recirculation	80	100
Exhaust	90	80
Exhaust flowrate (kg/s)	16	12

deliver sufficient cure to the product (flowrates at all points in the system omitted due to confidentiality).

Analysis of all process variables outlined that three fans (supply, recirculation and exhaust fans) had the largest impact on system air flow. Oven negativity ensures fumes stay within the oven and impacts the ingress of cold air into the oven, which has a detrimental effect on temperature distribution. The goal is to establish a fan setting to minimise system air flow while maintaining a very slightly negative pressure within the oven. Three experiments were conducted to achieve a minimum exhaust flow and a target slot flow. Table 1 displays the existing and optimised settings for the three process fans in the oven system. Here, the recirculation fan has been increased to maintain flow through the burner and the exhaust fan has been minimised. The optimal fan settings would decrease system exhaust flow by approximately 25 %, thus reduce gas energy consumption within the direct fired burners by 25 %. Uncertainty is due to the unpredictable nature of the oven negativity; affected by local atmospheric conditions and process temperature. Process optimisation has been demonstrated to save energy and reduce process temperature variability therefore enhancing product quality.

Optimal settings for key fans were identified which, along with insulating the inside of oven walls, reduce energy and develop temperature uniformity. Interaction between the three stages of the generic approach must be considered. In this study, it was ensured that reducing system airflow does not negatively impact on cure. Increased product understanding should allow for product quality to not be harmed, and hopefully improved, during process improvement and process parameter optimisation.

4 Recommendations

The approach outlined in this paper is adaptable to many scenarios and highlights the importance of establishing thorough product understanding before embarking on any modification plans. Assessing which process variables (e.g. oven pressure negativity) affect quality (e.g. product life) indicates areas of the possible improvement. It is also important to understand how the heat energy is required by the product. Oven performance should be evaluated to identify opportunities for process improvement by looking at: temperature uniformity, effect of thermal mass, equipment reliability etc.

5 Conclusion

This paper presents a general approach to industrial oven improvement which starts with developing product understanding, leading on to process improvement and finishing with process parameter optimisation. Improving the sustainability of ovens should be an important strategy for manufacturers due to their high energy consumption, effect on product quality and potentially hazardous work environment for employees. Such a methodology has not previously been applied to industrial ovens.

Generating product understanding identifies conditions necessary to create the desired product, thus highlighting areas of quality improvement. In the industrial case study presented, cure characterisation using DSC analysis of adhesive resin has been presented. The data showed that a feasible heating rate variation within the oven can result in dramatically different cure conversion when material exits the oven impacting on product quality and affecting economic and environmental dimensions of the oven. Process improvement involves ensuring the system hardware is performing well under the current process settings, while also establishing a way to enhance process capability. In the industrial case study, it was identified that the process could be improved by installing an insulation layer to the inside of the oven wall. This would result in 89 % reduction in heating and cooling times, saving 202 h of annual downtime. Process parameter optimisation alters the process settings to maximize performance. In the industrial case study, process parameter optimisation was conducted and identified fan setting that reduce energy consumption by minimising system flow and oven pressure negativity for better temperature uniformity and energy saving. The optimisation has reduced fuel gas consumption by 25 %.

This research looks to increase the sustainability of industrial ovens by improving the environmental and economic aspects of an industrial oven system. By providing an industrial case study example, the applicability of the proposed approach has been demonstrated. Further work is necessary to link product understanding to energy consumption, as this concept is a tool that can enable further sustainability enhancement in the manufacturing industry.

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Increasing Energy Potentials of Air-Jet Weaving Machines by Using Energy Efficiency as a Central Requirement in the Design Phase of the Weft Insertion Process

Corrado Grassi, Achim Schröter, Yves-Simon Gloy and Thomas Gries

Abstract The use of a novel method to exploit energy savings potentials in production processes of textile industry has been applied to the air-jet weaving technology. Energy efficiency is taken as central property in the design process and it represents a new requirement/property to be defined in the phase of design problem/task definition. In contradiction with established methodologies, the approach includes an initial analysis of existing technical systems and the individuation and classification of their prior and relevant energy consumers (sub-systems and processes). The identified major consumers and processes are afterwards systematically addressed to reduce their energy consumption: interaction of the relay nozzle flow field with the profiled reed. A following analysis step consists in the verification of the system design, predicting and evaluating the system behavior using several tools (e.g. finite element analysis, computational fluid dynamics simulations, experimental analyses, etc.). Since nowadays products become more and more multi-disciplinary by the constantly increasing integration of added functionality and product intelligence and since energy is a global design attribute which is influenced by all disciplines, the development of energy analysis methodologies, both numerical and experimental, able to decrease the environmental impact and to keep constant the machine performance requires an integrated

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research strategy. Therefore in next air jet weaving machine generations, the design process should move from a purely performance and capacity driven approach to an approach that includes energy efficiency as a key parameter.

Keywords Energy efficiency · Air jet weaving · Weft insertion · Machine manufacturing · Simulation and experimental analysis

1 Introduction

Air-jet weaving is a type of weaving in which the filling yarn is inserted into the warp shed with compressed air. Figure 1 shows a schematic of air-jet weaving utilizing a multiple nozzle system and profiled reed which is the most common configuration in the market. Yarn is drawn from a filling supply package by the filling feeder and each pick is measured for the filling insertion by means of a stopper. Upon release of the filing yarn by the stopper, the filling is fed into the reed tunnel via tandem and main nozzles. The tandem and main nozzle combination provides the initial acceleration, where the relay nozzles provide the high air velocity across the weave shed. Profiled reed provides guidance for the air and separates the filling yam from the warp [1]. A cutter is used to cut the yarn when the insertion is completed.

The air-jet weaving machine combines high performance (see Table 1) with low manufacturing requirements, because differently from rapier and projectile machines, the filling medium is just air and no mechanical parts are directly involved in the weft insertion process. It has an extremely high production rate up to 1.100 weft insertions per minute and it covers a wide range of processing yarns like spun and continuous filament yarns.

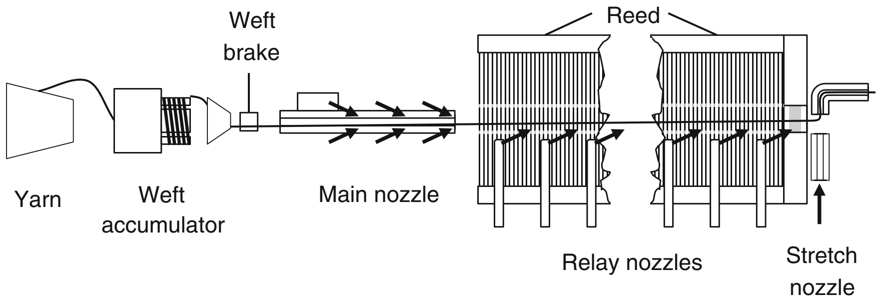

Fig. 1 Schematic view of air-jet weft insertion system

Table 1 General Characteristics of Air-Jet weaving machine

Air Jet weaving machine	
Weft Insertion rate (m/min)	2000
Average specific energy consumption (kWh/kg of woven fabric)	3–5

Table 2 Overview of the manufacturing costs of a woven fabric

	Brazil	China	Egypt	India	Italy	Korea	Turkey	USA
Waste	0.005	0.004	0.006	0.004	0.007	0.004	0.006	0.006
Labour	0.025	0.012	0.010	0.0130	0.206	0.082	0.074	0.130
Power	*0.075*	*0.083*	*0.035*	*0.093*	*0.156*	*0.051*	*0.091*	*0.052*
Auxiliary material	0.028	0.036	0.050	0.062	0.080	0.047	0.051	0.033
Depreciation	0.063	0.062	0.056	0.067	0.089	0.059	0.064	0.095
Interest	0.040	0.018	0.029	0.026	0.041	0.019	0.021	0.029
Total manufacturing costs (USD per meter of fabric)	0.236	0.215	0.186	0.265	0.579	0.262	0.307	0.345

Despite the very high production rate, the main drawback affecting negatively this technology is the very high energy consumption (see Table 2) due to compressed air demand which is required during the weft insertion process [5] and due to massive waste of such compressed, lost in the space between the reed metal strips without giving a contribution to the weft insertion process. Since the cost of energy has a systematic increasing trend, power consumption is still the most challenging issue for textile production machine manufacturers. In particular it is the limiting factor for such technology in the countries, where energy costs represents a large share of the manufacturing costs. An Overview of the manufacturing cost of a woven fabric can be seen in Table 2 [2].

For instance in Italy, the total manufacturing cost is 0.579 USD/m of woven fabric and power cost corresponds to 27 % (0.156 USD/m). In other countries such as India or China, the total manufacturing costs are less, respectively 0.265 USD/m and 0.215 USD/m, but on the other hand the power consumption is responsible respectively for 35 % (0.093 USD/m) and 38 % (0.083 USD/m) of the entire value.

At the purpose of decreasing the waste of compressed mass flow rate along the shed, a novel method based on energy efficiency as a central requirement in the design phase has been developed at the Institut für Textiltechnik der RWTH Aachen University (ITA), Aachen, Germany. Such method aims at increasing the energy efficiency of the machine by increasing the effective amount of mass flow rate which is directly involved in the weft insertion process. The increase of the mass flow rate in the air tunnel is rising the productivity of the machine while keeping constant the quality of the fabric. The study focuses on the interaction of the flow field coming out of the relay nozzles with the metal strips of the profiled reed. A detailed picture of the position of the relay nozzles and of the profiled is shown in Fig. 2.

Finally, the result of the research led to the investigation of the flow field throughout the shed and it gives a valuable insight for the design and development of a new air tunnel shape, able to decrease the waste of air and to provide higher

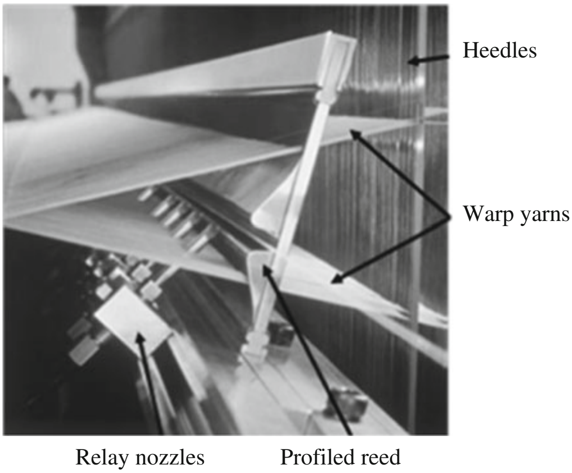

Fig. 2 Detailed view of the relay nozzle and the profiled reed

propulsive force to the filling yarn and therefore increasing the productivity of the machine. In this way, the high cost of the compressed air is justified by an achievement of higher value of the machine productivity.

2 Method

Increasing the energy efficiency of a production machine is one of the biggest challenges for the machine producer. The introduction of aspects of energy assessment into the process for the design of industrial machineries extracts useful elements from the field of the design theory. Theories and models of technical products and product development process have been in the focus of scientific work for roughly 40–50 years. Today, they are increasingly relevant also in industrial application (including machinery) because they are vital elements of current strategies such as concurrent/simultaneous engineering. Design for "X" (with "X" = strength, manufacturing, assembly, service, recycling, cost, etc.) is an important strategy especially in engineering design practice: the introduction of energy requirements into product specification can lead to define approaches of Design for energy efficiency.

Until now very few structured approaches for machinery design that take into account the energy impact of the resources have been proposed in the field of design theory and methodologies, and they have application limited to specific machine typology. Therefore an approach was developed at ITA especially for textile machines [6]. Established design methodologies have not yet considered energy efficiency as a central requirement of technical systems. As an inherent part of the methodology, it is necessary to take energy efficiency as a central

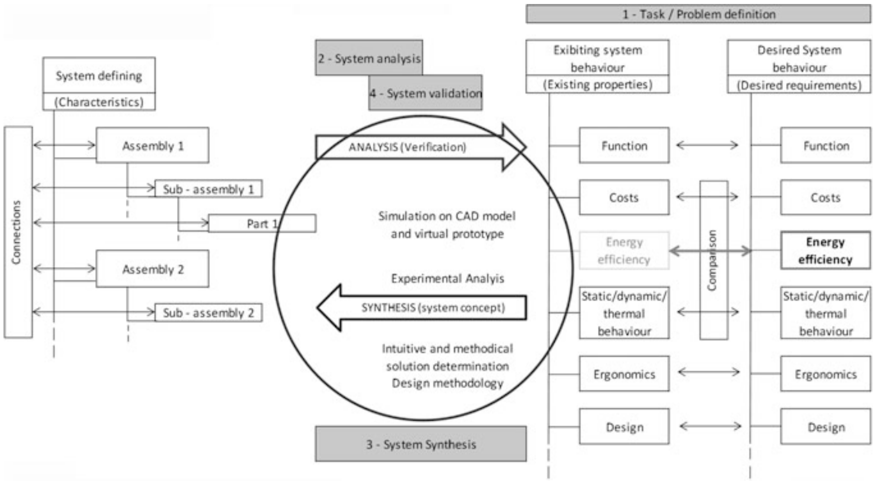

Fig. 3 Property-driven development by Weber

requirement into account, like the static, the dynamic or the thermal behavior of a machinery.

A systematic approach for the development of energy efficiency machine tools, proposed by Neugebauer [4], provides general concepts that can be applied to other type of industrial machinery and could be taken as reference in the possible definition of methodologies for the energy efficiency design of specific machines. This approach is based on the property-driven design methodology (see Fig. 3) by Weber [7], that defines the design process as a process which has to reach given properties (i.e. requirements) by defining characteristics to ensure this properties (e.g. geometries or materials).

Energy efficiency is taken as central property in the design process and represents a new requirement/property to be defined in the phase of design problem/task definition. In contradiction with established methodologies, the approach (see Fig. 4) includes an initial analysis of existing technical systems and the individuation and classification of their prior and relevant energy consumers (sub-systems and processes).

The identified major consumers are afterwards systematically addressed to reduce their energy consumption: several options and solutions—the system characteristics—are determined and considered, starting with the complete elimination of the energy usage and ending with the option of recovering energy. A following step of analysis consists of the verification of the system design, predicting and evaluating the system behavior using several tools (e.g. FEM analysis, simulation models, experimental analyses, etc.). The design process provides one or more solutions if the accounted properties are met by the defined characteristics.

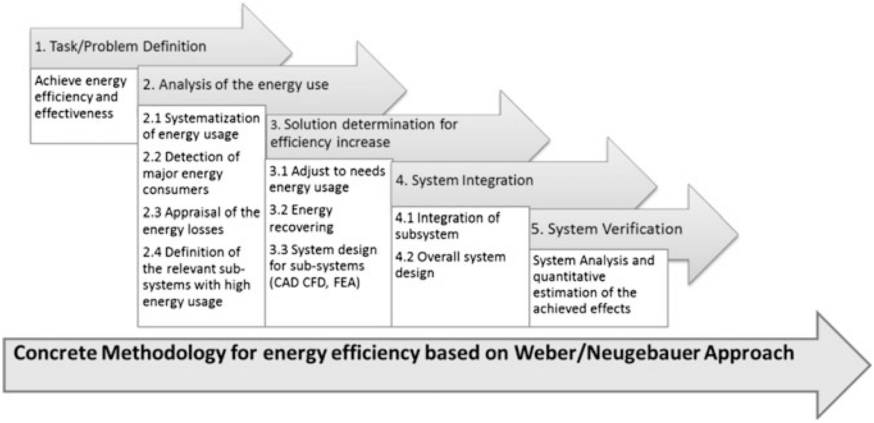

Fig. 4 Methodology for energy efficiency

Currently, the design of a machine is basically defined on the meeting of objective requirements and performance (production output, dynamic and kinematic properties, etc.) at the minimum cost. The idea at the base of this contribution is to propose energy-efficiency as a new additional and central property in the design process of a machine tool supported by specific methodologies. A systematic machine design approach has to take into account both the machine tool performance and the energy efficiency.

It must be noted that in general, energetic efficiency depends on how a machine is made ("design") and how it is used ("management"). These two aspects cannot be fully separated and a designer must take into account how the machine will be used and what will be the associated total cost of ownership and environmental impact. Since nowadays products become more and more multi-disciplinary by the constantly increasing integration of added functionality and product intelligence and since energy is a global design attribute which is influenced by all disciplines, the development of energy analysis methodologies, both numerical and experimental, able to decrease the environmental impact and to keep constant the product quality requires an integrated research strategy.

2.1 Application of the Method

When the filling yarn is inserted through the shed, it lies relatively far from its final position. This is because of the acute angle of the shed opening. Therefore, the newly inserted filling yarn needs to be brought to its final position by pushing through the warp sheet. Beat-up is the process of pushing the last inserted filling yarn to the cloth fell by using the reed. The reed is a closed comb of flat metal strips. These metal strips are evenly spaced at intervals that correspond to the spacing of warp ends in the fabric. Therefore the reed is also used to control warp yarn density in the fabric and weight as a consequence. The spaces between the metal strips are called "dents". After beating up the filling, the reed is withdrawn to its original rest position before the insertion of the next pick. The shape and thickness of the metal wires used in the reed are important parameter for the fabric features. Reed selection depends on several considerations including fabric appearance, fabric weight (ends per unit width), beat-up force, air space requirement and weave design. During the weft insertion process, most of the air injected by the relay nozzles (more than 50 %) leaks throughout the reed and only a small percentage of air, about 30 %, is actually accelerating the yarn and driving it to the receiving side of the machine. This matter turns into a large energy inefficiency of the machine by considering the unexploited amount of air that could improve the productivity of the air jet weaving machine in terms of weft insertion per minute and by taking into account the cost associated to the compressors in order to pump up most of the air that is not actually exploited. On a large industrial scale, such inefficiency mirrors into a relevant increase of the total cost of ownership of the machine. Therefore, at the purpose of justifying the high cost related to the compressed air, an investigation of the flow field along the reed has been carried out in order to reduce the waste of the mass flow rate leaking through the reed, respectively $\dot{m}_b$ and $\dot{m}_f$, in turn by increasing the amount of air which positively contributes to the yarn motion, $\dot{m}_c$ (see Fig. 5).

The propulsive force to move the yarn in the reed channel is provided by the friction between the air and the yarn surface and is given by the following Eq. (1),

$$F_f = \frac{1}{2}\, C_f\, \rho (U - V)^2\, \pi\, D\, L \tag{1}$$

C_f skin friction coefficient
P air density
U air velocity
V yarn velocity
D yarn diameter
L yarn length subject to air, yarn characteristic length.

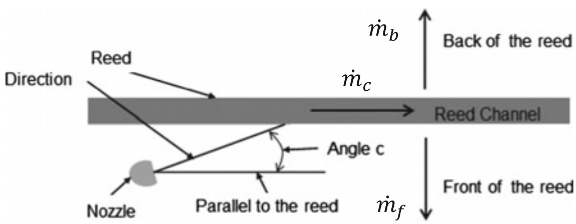

Fig. 5 Theoretical model of the weft insertion process in air jet weaving machines

This force is proportional to the square of the relative velocity between the air stream and yarn. The propelling force increases with grow of the air velocity and it depends on the amount of mass flow rate coming out from the relay nozzles too. To increase the value of mass flow rate in the reed channel means to increase the productivity of the machine.

Assuming the further hypothesis:

- Steady state flow
- Negligible yarn flexibility
- Constant yarn velocity across the shed
- Interaction of air through the reed dents.

The thrust provided by the relay nozzles to the yarn is the key point for the productivity of the machine and for the quality of the product. To rise this value would mean to increase the friction force which is actually the propelling force acting on the yarn and responsible of the fabric production rate.

The study carried out at ITA gave a valuable intuition to build up a new geometry of the metal strip, based on the aerodynamic duct theory in order to minimize the amount of waste air and in turn to maximize the number of weft insertion per minutes. Characteristic of this new shape is the more enclosed structure which prevents air to get out of the reed and it fosters an increase of the mass flow rate which is really participating to the propulsive force on the yarn. By employing the new concept of metal strip, the velocity of the yarn, which is currently in the state of the art between 55 and 80 m/s, is increased and the weft insertion rate per minute rises of 10 %. The model in Fig. 5 is a reasonable first approximation and it gives an insight to understand the physics of the air jet weft insertion process. Consequently, deep aerodynamic simulations have been carried out in order to validate the theoretical model and to provide a more faithful representation of the flow field coming from the relay nozzles along the shed.

3 Results

For the validation of the theoretical model different, flow simulations have been carried out. The simulations are done with the Computational Fluid Dynamics (CFD) simulation tool ANSYS Fluent from ANSYS, Inc., Canonsburg, USA. Within the simulation the flow field along the shed and the interaction with the reed is simulated and analyzed. The simulation is based on the following assumptions:

- Compressible flow field, ideal gas, steady state flow

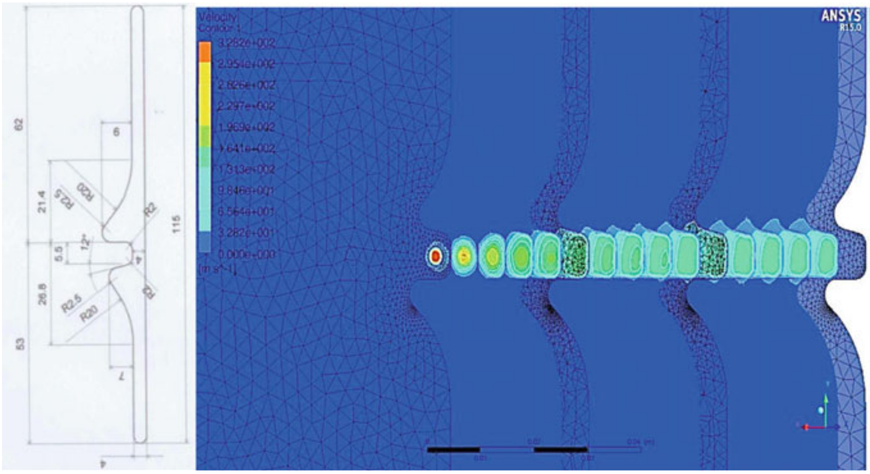

Fig. 6 Shape of the metal strip and flow field simulation along the air tunnel

With these assumptions a CFD model was set up and a CAD-model was integrated into this model. Downstream of nozzles is a free flow field with ambient pressure. The CFD model with the simulated flow field is shown in Fig. 6.

The air stream that lies in the air tunnel escapes from the acceleration region of the yarn not only towards the forward open side of the reed channel, but also through the back. According to the fluid-dynamic theory, the air flows quite in the middle of the channel. Moreover it can be drawn by means of the simulations that the walls of the metal strips behave as a suction sink for the flow field which is forced to vanish through the dents of the reed. The velocity circles identify the velocity flow field and by going along the shed it can be seen that such circles move towards the wall, between the void spaces in the dents. Such air afterwards therefore is wasted and no longer able to go inside the shed again and to accelerate the yarn. Starting from the state of the art metal strip shape and taking into account the results gained by means of flow field simulation, a new geometry of metal strip has been therefore developed in order to cope with this issue (see Fig. 7).

This new more enclosed shaped metal strip is capable to hold an higher quantity of air inside the air channel and therefore to increase the friction with the yarn. The rise in the friction force mirrors into an increase of the number of picks per minute. In this way, the costs associated to the compressors can be better justified, since more air is remaining in the air channel and the productivity of the machine increases of a factor 10 %.

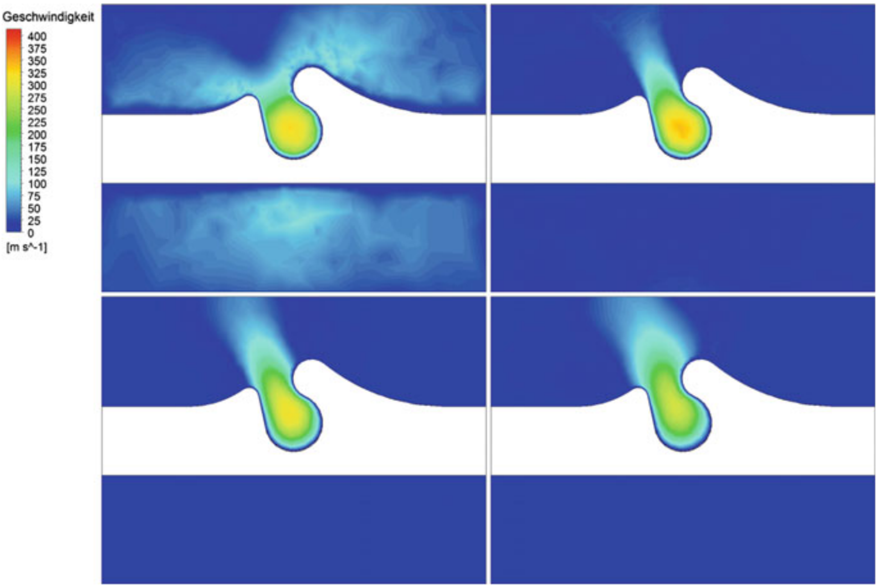

Fig. 7 New shape of the metal strip which enables potential savings of compressed air

4 Discussion

The simulation of the flow field along the shed show that energy savings are possible by employing a new metal strip shaped geometry. Such geometry prevents air to vanish towards the front of reed and it enables a rise of the machine productivity. The enclosed geometry gives an higher thrust to the yarn which mirrors in a rise of 10 % of weft insertion picks per minute. Within the weaving process, the reed has a relevant influence on the flow field; therefore the investigation of the flow field carried out in this study, gives a relevant remark to use potential new geometries of profiled reed. Nowadays, considering the weaving process, the relay nozzles employ 5 bar in overpressure: by combining this study on the reed with the investigation carried out on the relay nozzles, another noticeable remark can added to justify the reduction of the inlet pressure in the relay nozzles, since such rise in the pressure is made basically just to increase the mass flow rate in the air-channel. Of course the flow field out of the nozzles is strictly connected to the flow behavior in the reed and other studies have been made at ITA concerning this matter [5].

Eventually, by using the new shape of metal strips in combination with a new concept of relay nozzles able to operate at a lower value of inlet pressure, not only the productivity of the machine is improved but also the costs associated to pump up the air are reduced. The use of smaller compressors (see Table 3) enables a relevant reduction of the energy consumption of the weaving machine, without negatively affecting the quality of the fabric.

Table 3 Energy consumption of a compressor depending on the operating pressure

Operation pressure (bar)	Energy consumption (kW/m^3/h)
1	*2800*
2	3560
3	4120
4	4720
5	*5350*

In the case of 5 bar operating pressure the compressor has an energy consumption of 5.35 kW/m^3/h. If the operation pressure will be reduced to 1 bar, the energy consumption is 2.8 kW/m^3/h. By employing the combination of new shaped reed with a new concept of relay nozzles able to operate at 1 bar, energy potential can lead up to 30 % savings.

5 Conclusion

At the Institut für Textiltechnik der RWTH Aachen University, Aachen, Germany a novel method has been developed to identify potentials in saving energy of textile production processes [6]. The air-jet weaving process is the most productive but also the most energy intensive weaving process. By placing energy efficiency as a central requirement in the design phase of the machine, the most energy demanding processes and the components are identified and analysed. Based on a theoretical model of the weft insertion, a new concept for the metal strips of the profiled reed has been drawn. The new metal strip enables an higher quantity of air to remain longer in the air tunnel where the filling yarn is flying. Such increase of mass flow rate turns into an improvement of the machine performance, 10 % in terms of weft insertion picks per minute. Moreover, such new geometry allows the use of new relay nozzles concept which are able to operate at a reduced inlet pressure value. By combining the application of new profiled reed with new concept of relay nozzle able to operate at 1 bar, not only the total costs of machine ownership are reduced but also the productivity is increased. By means of CFD simulations, this study gives a first insight on how to improve the usage of compressed air during the weft insertion process. The next step is the validation of the new profiled reed concept before by means of a test bench and afterwards on a larger scale within the real weaving process.

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Modelling and Verification of Energy Consumption in CNC Milling

A. Shokrani, V. Dhokia and S.T. Newman

Abstract Electrical energy consumption forms 99 % of the environmental impact of machining operations. Whilst replacing existing machineries for more energy efficient ones does not deem possible in short term, process planning for machining with energy consumption in mind is a more accessible solution. The effect of cutting parameters on power consumption in CNC milling of 6082 T6 aluminum alloy was investigated in this paper. Mathematical models were developed to estimate the energy and power consumption in CNC milling machines. The analysis indicated that the two less studied parameters of axial and radial depth of cut have significant impact on the total energy consumption of machining processes. Increased axial and radial depth of cut not only increase material removal rate but also increase the portion of machine tool's power consumption dedicated to material cutting. This study indicated that 82 % reduction in energy consumption can be achieved through precise selection of cutting parameters.

Keywords Energy consumption · CNC machining · Milling · Power consumption · Aluminum

1 Introduction

Manufacturing is responsible for 25 % of the global energy consumption [1]. Knowing that a significant portion of the electricity is generated using fossil fuels such as oil and coal, manufacturing and in particular machining are responsible for the generation of a large portion of CO_2, NO_2, SO_2 and other pollutants [2]. It has

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been reported that electrical energy consumption is responsible for 99 % of the environmental impacts of machining operations.

Kant and Sangwan [3] defined sustainable machining processes as using the minimum power consumption. Time is directly related to energy consumption as shown in Eq. 1; therefore this notion of sustainability implies that all machining operations will be more energy efficient if the power requirements for all components are reduced. Also, faster tool path designs will generally result in lower energy consumption. Faster tool paths are also consistent with a better surface finish [4]. Energy efficiency is defined by the lowest energy consumption, which is not necessarily correspondent to the lowest power consumption.

$$E = \int_{t_0}^{t} P dt \tag{1}$$

where E is energy in J, P is power in W and t is time in s.

There have been many attempts to formulize a mathematical model for estimating energy consumption for different manufacturing techniques [5–7]. Some derived models produce large degrees of inaccuracy, up to two orders of magnitude, whereas others include so many coefficients requiring such extensive empirical results, that often quantifying power consumption specifically is easier than modelling. Li and Kara [8] studied cutting speed, feed rate and axial depth of cut and developed an empirical model relating the specific energy consumption to material removal rate as shown in Eq. 2.

$$SEC = C_0 + \frac{C_1}{MRR} \tag{2}$$

where SEC is specific energy consumption, C_0 is the coefficient of the inverse model and C_1 is the coefficient of the predictor.

A great deal of studies has been conducted on modelling of the cutting forces and power demand at the tool tip dealing with science of machining [6]. These models have shown that there is a relationship between the energy required for machining and the workpiece material properties and cutting parameters [9]. The specific cutting energy of various materials are used to model the energy demand at the cutting tool tip [10]. The specific cutting energy defines the amount of energy required for machining a unit volume of material. However, these material specific models do not consider the amount of energy which is required for running a machine tool. The studies by Aramcharon and Metivenga [4] and Gutowski et al. [11] indicated that the machine tools' idle energy consumption is a single significant factor affecting the total machining energy consumption. Therefore, they recommended reducing the none material cutting time during machining and optimizing the machine tools to minimize their power consumption when running idle [12].

This paper investigates the effects of cutting parameters on energy and power consumption in end milling of 6082 T6 aluminium alloy. Four major cutting parameters in milling operations namely, cutting speed, feed rate, axial depth of cut and radial depth of cut in machining are studied in this paper.

2 Methodology

In order to assess the effect of each machining parameter on the total energy consumption, four input parameters of cutting speed, feed rate, axial depth of cut and radial depth of cut were identified. A TiB_2 coated solid carbide end mill with 12 mm diameter and 2 flutes was used for each machining experiment. The workpiece used for each experiment was a block of 6061 T6 aluminum with the dimension of 150 × 50 × 50 mm as shown in Fig. 1.

In order to include the interactions between parameters, a full factorial design of experiments (DoE) was developed based on 2 levels of cutting speed and feed rate and 3 levels of axial depth of cut and radial depth of cut. Further emphasis was put on the axial and radial depth of cut as these are the least studied parameters in machining. The three levels of the axial depth of cut correspond to 0.5D, D and 1.5D, where D is the cutting tool diameter. For the radial depth of cut, 30 % (3.6 mm), 45 % (5.4 mm) and 60 % (7.2 mm) cutting tool engagement were used. The DoE used for this investigation consisted of 36 machining experiments as shown in Table 1.

The machining experiments were side end milling in order to remove an 18 mm depth of material from the top surface of the aluminum blocks as shown with hatched lines in Fig. 1. This would allow for identical comparison of machined volume of material between experiments. The machining strategy was climb milling using unidirectional tool paths along the length of the workpiece starting the feed move 10 mm before the workpiece material continuing 10 mm after. Rapid

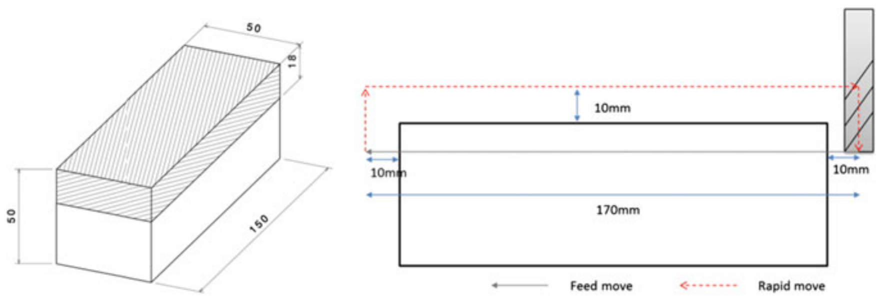


Fig. 1 Illustration of the workpiece used for the machining experiments with hatched machining volume (*right*) and the machining process plan

Table 1 DoE for machining experiments

Exp	a_e (%)	a_p (mm)	f (mm/tooth)	v (m/min)	Exp	a_e (%)	a_p (mm)	f (mm/tooth)	v (m/min)
1	60	18	0.08	70	19	30	9	0.09	70
2	60	18	0.08	90	20	30	9	0.09	90
3	60	18	0.09	70	21	30	6	0.08	70
4	60	18	0.09	90	22	30	6	0.08	90
5	60	9	0.08	70	23	30	6	0.09	70
6	60	9	0.08	90	24	30	6	0.09	90
7	60	9	0.09	70	25	45	18	0.08	70
8	60	9	0.09	90	26	45	18	0.08	90
9	60	6	0.08	70	27	45	18	0.09	70
10	60	6	0.08	90	28	45	18	0.09	90
11	60	6	0.09	70	29	45	9	0.08	70
12	60	6	0.09	90	30	45	9	0.08	90
13	30	18	0.08	70	31	45	9	0.09	70
14	30	18	0.08	90	32	45	9	0.09	90
15	30	18	0.09	70	33	45	6	0.08	70
16	30	18	0.09	90	34	45	6	0.08	90
17	30	9	0.08	70	35	45	6	0.09	70
18	30	9	0.08	90	36	45	6	0.09	90

moves were used for all none material cutting movements. The details of the machining process plan are shown in Fig. 1.

A Bridgeport VMC 610 vertical CNC milling center was used to conduct the machining experiments. The machine tool was equipped with a Hioki Clamp-on Tester power demand analyzer with a sampling rate of 1 s. The power consumption of the machine tool was monitored for the duration of the machining experiment. The energy consumption of the machine tool was calculated from the power consumption using Eq. 1. In order to eliminate the effects of coolant pump on the power consumption, a minimum quantity lubrication system with vegetable oil at the rate of 70 ml/h at 6 bar pressure was used.

3 Results

After machining experiments, the data for power consumption was collected for each experiment. Figure 2 illustrates the power consumption graph for experiment 1 and indicates the critical points for power consumption of idle, rapid move and feed without material cutting and with material cutting. Since the radial width of cut for experiment 1 was 60 % (7.2 mm) and the depth of cut was 18 mm, only 7

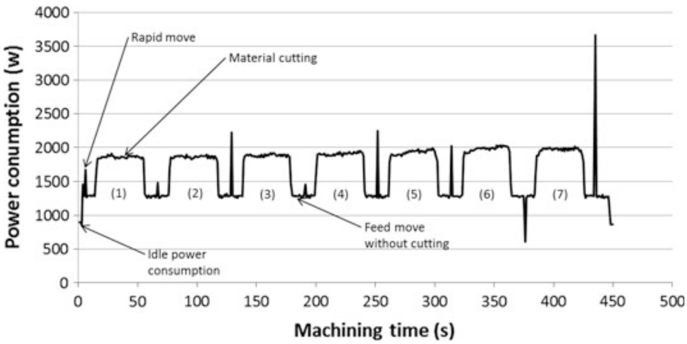


Fig. 2 Power consumption graph for experiment 1

machining paths were required in order to achieve the objective of the experiment (machining 18 mm depth of workpiece) as shown in Fig. 2.

By definition, the area below the power consumption represents the total energy consumption of the machining process including none material cutting moves inherent to machining. Using Eq. 1, the energy consumption of the machining process for each experiment was calculated and illustrated in Fig. 3.

The power consumption of the none material cutting moves were removed from the data for power consumption and the average power consumption for cutting material was also calculated. The results of the average power consumption for material cutting are shown in Fig. 3.

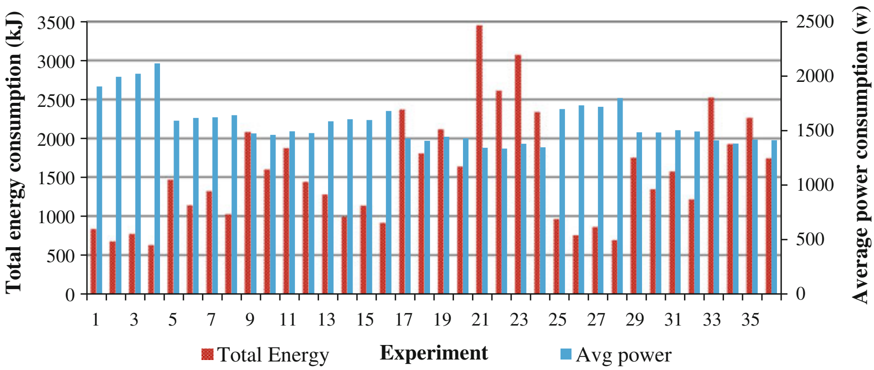


Fig. 3 Energy consumption and power consumption graphs of the experiments

4 Analysis and Discussion

The main effect plot and interaction plots were generated for the data presented in the results section. As shown in Fig. 4, the analysis indicated that increased productivity through adoption of higher levels of feed rate, cutting speed and axial and radial depth of cut reduces the energy required for machining a part. This is in agreement with previous studies stating that enhanced material removal rate reduces the energy consumption. Analysis of the results indicated that about 890 W power is required to run the machine tool. This equates to 42–66 % of the total power consumption of the machine tool for cutting material based on the parameters used in this study. Referring to Eq. 1, reducing the machining time through increased material removal rate can significantly decrease the total energy consumption.

The analysis of the energy consumption results indicated that there is no significant interaction between the input parameters within the studied range. Furthermore, they indicated that almost 82 % reduction in energy consumption can be achieved by precise selection of the cutting parameters.

As shown in Fig. 5, all cutting parameters have significant effect on power consumption whilst no significant interaction was found between the parameters. Axial and radial depth of cut were identified to be more significant in this study. As opposed to the energy consumption, power consumption can only be reduced by 37 %. This can be explained by the fact that a significant portion of the power consumption is used for running the machine tool which is not affected by the cutting parameters. Moreover, the effect of cutting speed and feed rate is more significant on the machining time and therefore energy consumption than on the power consumption.

In addition to the power consumption of the machine tool when cutting material, the power consumption when a material is not being cut was also measured. Deducting 890 W power consumption of the machine tool in idle mode, this would highlight the power consumption for running the spindle and servos at given feed rates and cutting speeds. Figure 6 illustrates the percentage of power consumption dedicated to cutting material for each machining experiment as compared to the

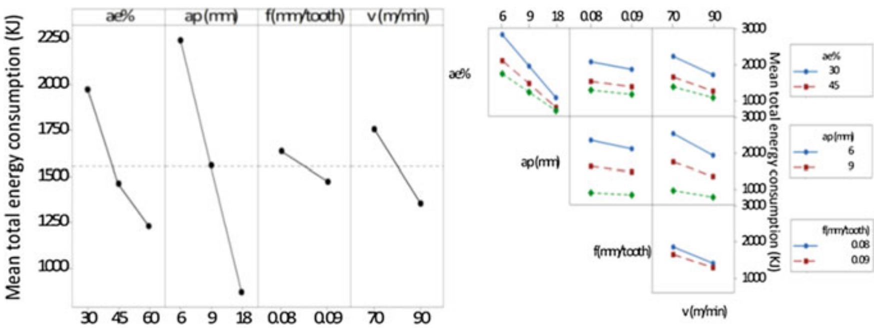


Fig. 4 Main effect plot (*left*) and interaction plot (*right*) for total energy consumption

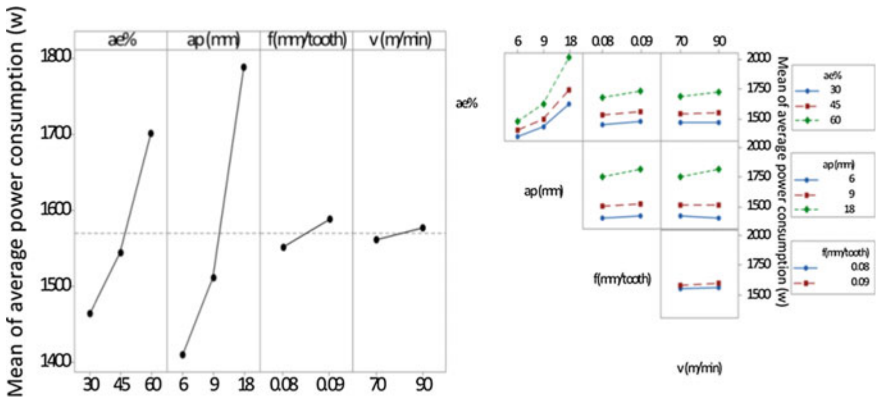


Fig. 5 Main effect plot (*left*) and interaction plot (*right*) for power consumption

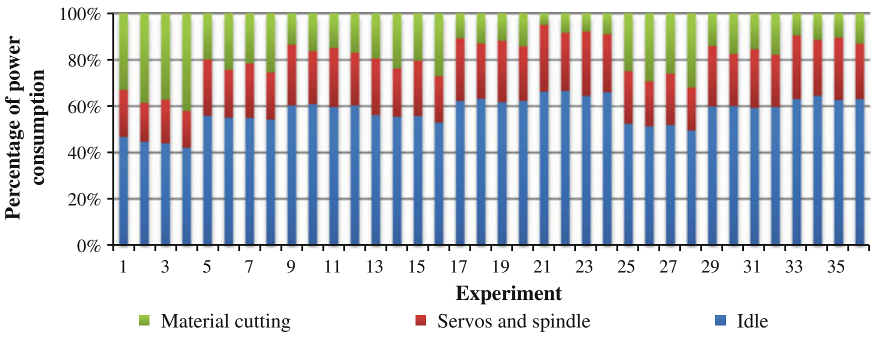


Fig. 6 Comparison between power consumption for material cutting, running servos and spindle and machine tool's idle state

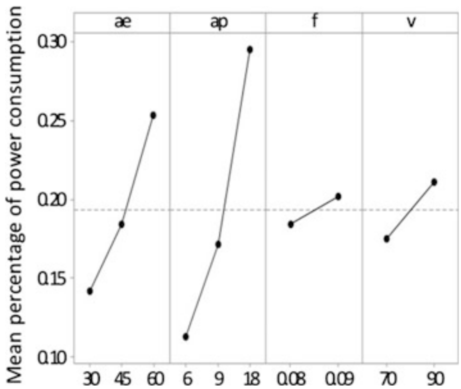
power used for running the machine tool in idle mode and servos and spindle. This graph shows that a very small portion of the power consumed by the machine tool is used for cutting material. Compiling this data indicated that, depending on the cutting parameters, only 4.9–42.1 % of the machine tool's power consumption is used for cutting material.

Figure 7 demonstrates the relative power consumption for cutting at worst case scenario in experiment 21 where all input parameters are minimum. Moreover, the best case scenario is attributed to the experiment 4 where all input parameters are at maximum level. As shown in Fig. 7, on average, only 19.3 % of the total power consumption is used for material cutting whilst 57.5 % is used for running the machine tool.

Analyzing the power consumption indicates that higher levels of cutting parameters are more desirable in order to maximize the percentage of the power dedicated to material cutting. As shown in Fig. 8, higher cutting loads through

Fig. 7 Dynamic breakdown of the power consumption by Bridgeport VMC 610 based on the results

Fig. 8 Main effect diagram of percentage of power consumption used for material cutting



employing larger depth of cut and cutting speed increases the contribution of material cutting into the machine tool's power consumption. This is in agreement with the analysis for energy consumption and indicates that machining time is not the only major factor for selecting higher levels of material removal rates.

Material removal rate (MRR) was calculated using Eq. 3 for each experiment.

$$MRR = \frac{1000\, n\, a_p\, a_e\, v f}{D\pi} \tag{3}$$

where MRR is material removal rate in mm^3/min, D is cutting tool diameter in mm, n is number of teeth, a_p is axial depth of cut in mm, a_e is radial depth of cut in mm, v is cutting speed in m/min and f is feed rate in mm/tooth.

As shown in Fig. 9, the average power consumption is in an almost linear relation with MRR. On the other hand, total energy consumption is in an inverse relation with MRR. Therefore, regression analysis was performed in order to

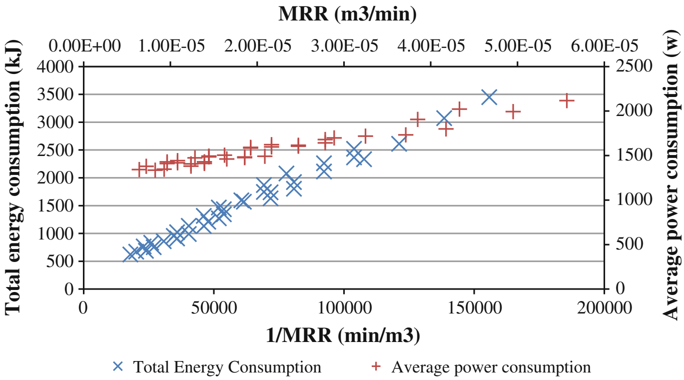


Fig. 9 Total energy consumption and average power consumption graphs versus MRR

develop a mathematical model for each parameter in order to estimate the values based on MRR.

Equations 4 and 5 illustrate the regression models for total energy consumption and average power consumption.

$$E_t = 270.6 + \frac{0.02043}{MRR} \quad (4)$$

$$P_a = 1237 + 15536354\,MRR \quad (5)$$

where E_t is total energy consumption and P_a is average power consumption.

Analysis of variance for the generated models indicated that the models are capable of estimating experimental values to a very high accuracy. As shown in Table 2, the model for total energy consumption explains about 98 % of the variation in energy consumption. Similarly, the model for average power consumption fits 95 % of the experimental data. The regression model for total energy

Table 2 Analysis of variance for the regression models of total energy consumption and average power consumption

Total energy consumption					
Source	DF	SS	MS	F	P
Regression	1	17131486	17131486	2181.23	0.000
Error	34	267037	7854		
Total	35	17398523			
R^2 = 98.5 % adjusted R^2 = 98.4 %					
Average power consumption					
Source	DF	SS	MS	F	P
Regression	1	1316115	1316115	661.32	0.000
Error	34	67664	1990		
Total	35	1383779			
R^2 = 95.1 % adjusted R^2 = 95.0 %					

consumption is similar to the model suggested by [6]. However, they did not identify the linear relation between average power consumption and MRR. Dividing the E_t would provide an estimation for specific energy consumption for the Bridgeport VMC 610xp machine tool.

Equation 3 for MRR can be incorporated into the mathematical models in Eqs. 4 and 5. Following suggestions by Li and Kara [8] and substituting the models' coefficients with generic machine tool dependent variables result in a milling specific model relating cutting parameters and cutting tool diameter to total energy consumption and average power consumption.

$$E_t = C_0 + \frac{C_1 D\pi}{1000 n a_p a_e v f} \tag{6}$$

$$P_a = C_2 + C_3 \frac{1000\, n\, a_p\, a_e\, v f}{\mathrm{D}\pi} \tag{7}$$

The investigations by Li and Kara [8] together with the investigations presented in this paper has shown that the coefficients of the models in Eqs. 6 and 7, namely C_0, C_1, C_2 and C_3 are machine tool dependent variables. These coefficients can be used for assessing the environmental performance of various machine tools and can be supplied by the manufacturers for energy labeling of the machine tools.

5 Conclusions

A series of machining experiments were conducted to investigate the effect of cutting parameters on power and energy consumption. A systematic methodology was developed using a full factorial design of experiments using four input parameters of cutting speed, feed rate, axial depth of cut and radial depth of cut. The analysis of the results showed that minimizing machining time by employing higher material removal rate is desirable for reducing total energy consumption. However, the investigations indicated that machining time is not the only factor for improving machining efficiency. The amount of power used for cutting material forms a limited portion of the total machining power consumption as opposed to the power required for running the machine tool without cutting material. Therefore, increasing the percentage of the power used for cutting can increase the efficiency of machining. It has been identified that by precise selection of cutting parameters, 82 % reduction in total energy consumption can be achieved.

Mathematical equations were developed which can accurately estimate the total energy consumption and average power consumption of a CNC milling machine tools. The coefficients of these models can be used for assessing and rating the energy performance of machine tools.

Furthermore, the data collected for this experiment will be used for developing and validating a mathematical model representing all cutting parameters involved in milling operations. This model will provide a guideline for energy efficient process planning in CNC milling.

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Optimal Cutting Parameters to Reduce Power Consumption in Face Milling of a Cast Iron Alloy for Environmental Sustainability

Xiaona Luan, Song Zhang and Gaoli Cai

Abstract In the perspective of energy saving, the power consumption in the process of CNC (Computer numerical control) machining is closely related to the environmental issues. Therefore, it is especially important to optimize the cutting parameters to reduce the power consumption. In this paper, the power consumption which is determined by the cutting parameters in the face milling process of a cast iron alloy is researched. First, characteristics of machine tool power consumption were studied and the relationship between power consumption and cutting forces was described qualitatively. Secondly, a power consumption monitoring system was built to monitor and record the power consumption in real time during a face milling process. Secondly, according to central composite design (CCD), a total of 27 experiments were carried out to reveal the relationship between the power consumption and process parameters. Finally, the milling parameters were optimized by means of response surface methodology (RSM). The results indicate that the power consumption of P_M and P_Y can be saved by 38.55 and 28.23 % under the cutting condition of optimized parameters, and the surface quality is insured simultaneously.

Keywords Power consumption · Optimization · Cutting parameters · A cast iron alloy · Face milling

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1 Introduction

The improvement of environment and energy efficiency is associated with development of industry technology. Power efficiency, as a global concept in the engineering field, has been focused on by both the company and government while it can influence the environment directly or indirectly [1]. Previous research showed that two-thirds of the power energy is used in industry field in China. Therefore, the research about power efficiency is becoming considerably important [2].

During metal removal process, relative motions between the cutting tool and the workpiece are realized by main motor and servo motors, which can provide power and torque by consuming electricity. If a component of machine system lacks dynamic stiffness or damping, displacements and forces become higher at each tooth pass and the process becomes unstable [3]. So servo motors are used in a control loop system for these error compensations and consume little electricity during the machining process.

The previous researches pointed out that power consumption is associated with many conditions [4, 5]. Some research has been conducted to evaluate the environmental impacts of machining [6, 7]. In general, the methodologies of energy-efficient modeling of machining systems can be divided into three different levels: machine tool level, component level, and system level [8]. Bi and Wang pointed out that machining energy usage is solely based on specific cutting energy [9]. In order to understand and evaluate the specific cutting energy, the therblig-based energy supply modeling was proposed [10]. Mesquita et al. [11] established an approach to optimize the cutting parameters in turning in order to minimize the production cost and machining time. Response surface methodology (RSM) was widely used in the fields of optimization of cutting parameters [12], power consumption and tool life [13].

Metal removal process is realized by spindle motion and feed motions, and power consumptions of these motions vary from different combination of cutting parameters. Dividing total power into each axial motor's power is benefit for analyzing power consumption of specific motor during machining process and could accurately find large-power machining steps, and then optimized them. By now, few researches investigated real time power consumption of spindle motion and feed motions' driven axis.

The objective of the present research is to find the influence of cutting parameters on power consumption, and then optimized to decreasing the power consumption by RSM. First, the relationship between power consumption and cutting forces was described qualitatively. Secondly, according to central composite design (CCD), a total of 27 experiments were carried out to reveal the relationship between the power consumption and cutting parameters. Finally, the milling parameters were optimized by RSM to minimize the power consumption.

2 Relationship Between Power Consumption and Cutting Force

2.1 Characteristics of Machine Tool Power Consumption

The power consumption of machine tool is usually divided into two components, the cutting power consumption which is caused by removing material and the auxiliary power consumption which is caused by auxiliary equipment during idle process. Cutting power consumption is variable which is related to the material properties, cutting parameters, cutting conditions and tool conditions. There is a complex dynamic interaction and coupling effect between these relevant variables. Power consumption curve is usually made up with dynamic balance equation and stationary state equation alternately, which can be expressed as follows:

$$f_{pi}(t) = \begin{cases} P_i^{\mathrm{D}}(t) & i \in \{\mathrm{D}\} \\ P_i^{\mathrm{U}}(t) & i \in \{\mathrm{U}\} \\ P_i^{\mathrm{C}}(t) & i \in \{\mathrm{C}\} \end{cases} \tag{1}$$

where $P_i^{\mathrm{D}}(t)$ is the input power consumption function of the machine tool starting/braking, $P_i^{\mathrm{U}}(t)$ is the idling power consumption function during the engage and retract process, $P_i^{\mathrm{C}}(t)$ is the input power consumption function of the machining process.

2.2 Power Modeling Method of the Three Types Consumption

The power consumption of machine tool starting/braking $P_i^{\mathrm{D}}(t)$, idling process $P_i^{\mathrm{U}}(t)$, and material removing process $P_i^{\mathrm{C}}(t)$ has their own characteristics and different influencing factors. $P_i^{\mathrm{D}}(t)$ and $P_i^{\mathrm{U}}(t)$ are influenced by the characteristics of machine tool, while $P_i^{\mathrm{C}}(t)$ has some correlation with cutting parameters cutting condition. So the mathematical models of them are studied respectively as follows.

(1) Input power consumption function of the machine tool starting/braking $P_i^{\mathrm{D}}(t)$.

The process of machine tool starting/braking is usually unstable, which makes building of the dynamic balance equation more complex and difficult. But during starting, there’s no cutting power, and $P_i^{\mathrm{D}}(t)$ is decided by the structure of machine tool itself and has no effect of the workpiece. When a machine tool is working in a certain speed, the idling power is always constant. In another word, idling power consumption curve during the engage and retract process is almost a straight line. Besides, the value of idling power has no relation with the workpiece. Then the method of building $P_i^{\mathrm{U}}(t)$ is similar with the $P_i^{\mathrm{D}}(t)$, and the sample database of $P_i^{\mathrm{U}}(\mathrm{t})$ is built up based on some experimental data in different spindle speed n.

(2) Idling power consumption function during the engage and retract process $P_i^{\mathrm{U}}(t)$.

A machine tool idling feature could be expressed by the following equation, which is a stationary state function correlated with the spindle speed n, then $P^{\mathrm{U}}(t) = P^{\mathrm{U}}(n)$.

When a machine tool is working in a certain speed, the idling power is always constant. In another word, idling power consumption curve during the engage and retract process is almost a straight line. Besides, the value of idling power has no relation with the workpiece. Then the method of building $P_i^{\mathrm{U}}(t)$ is similar with the $P_i^{\mathrm{D}}(t)$, and the sample database of $P_i^{\mathrm{U}}(t)$ is built up based on some experimental data in different spindle speed.

(3) Input power consumption function of the machining process $P_i^{\mathrm{C}}(t)$.

Power consumption during face milling process is usually calculated by the following function $P_i^{\mathrm{C}}(t) = P_{ui}(t) + \alpha P_{ci}(t)$. Where $P_{ui}(t)$ is power of auxiliary equipment, and value of $P_{ui}(t)$ is just a constant. $P_{ci}(t)$ is cutting power function. The feature of $P_i^{\mathrm{C}}(t)$ is similar with $P_{ci}(t)$, So study of $P_{ci}(t)$ is very important.

The cutting power consumption $P_{ci}(t)$ can be divided into three parts, i.e., cutting power of spindle P_{m}, power of feed motion P_{f}, and power consumed by auxiliary systems P_{ux} and P_{uz}. P_{m} and P_{f} are affected by the cutting parameters and workpiece material. So they could be decreased by optimizing the cutting parameters. As shown in Fig. 2, during the face milling process, the cutting force change with the chip thickness decreasing from the maximum to zero over a spindle revolution. In the process of material removal, the tool tooth has to withstand instantaneous tangential component F_{t}, instantaneous radial component F_{r}, and instantaneous axial component F_{a} (cutter system) [14]. Once three force components F_{x}, F_{y}, and F_{z} acting on the face milling cutter (table system) in the Cartesian coordinate system are determined by experimental results, three cutting forces F_{t}, F_{r}, and F_{a} (cutter system) on the tooth-workpiece contact point can be expressed through a coordinate transformation.

$$\begin{bmatrix} F_{\mathrm{t}} \\ F_{\mathrm{r}} \\ F_{\mathrm{a}} \end{bmatrix} = \begin{bmatrix} -\sin\varphi(t) & \cos\varphi(t) & 0 \\ \cos\varphi(t) & \sin\varphi(t) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} F_{\mathrm{x}} \\ F_{\mathrm{y}} \\ F_{\mathrm{z}} \end{bmatrix} \quad \varphi_{\mathrm{st}} < \varphi(t) < 180^\circ \tag{2}$$

During face milling process (Fig. 1), the milling cutter made a feed motion along Y direction, the motion velocity along X and Z direction was zero. The feed rate was very slightly, and the power consumption of feed motion P_{f} was small which caused by F_{y}.

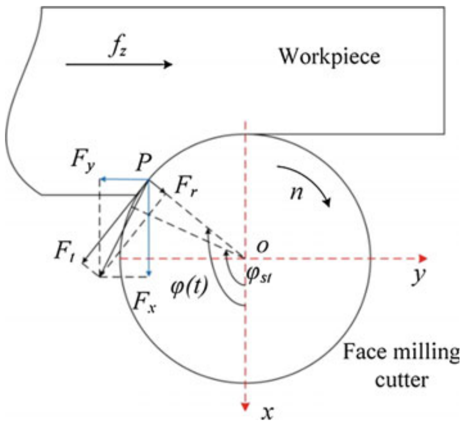

Fig. 1 Schematic view of face milling process

$$P_f = F_y \cdot v_f = F_y \cdot nf_z \quad (3)$$

where F_y is cutting force component along direction of feed (cutting system), v_f is feeding speed (m/min).

The cutting power of spindle P_m is related with the main cutting force F_t.

$$P_m = \frac{F_t \cdot v_c}{1000 \times 60} = \frac{F_t \cdot 2\pi nR}{1000 \times 60} \text{ (W)} \quad (4)$$

where F_t is instantaneous tangential component (N), v_c is cutting speed (m/min), n is the spindle speed (r/min), R is the radius of face milling cutter (mm).

3 Experimental Details

3.1 Workpiece Material, Cutting Tool and Machine Tool

The material of workpiece is a cast iron alloy, which added a small quantity of alloy element Cu, Cr and Sn into the conventional cast alloy HT-250. Rectangular blocks of the workpiece were prepared in the dimensions of 100 × 50 × 25 mm and the surface materials of workpiece were removed. Cutting tools used in the experiments were Seco face milling cutters (F40M) and tool holder was Seco R220.43-0063-07W whose diameter reached 63 mm.

The face milling experiments were performed on a three-axis vertical machining center (Daewoo, ACE-V500) under dry conditions, which has a total power of 30 kW. The main spindle, X, Y, and Z axis are driven by four motors whose rated

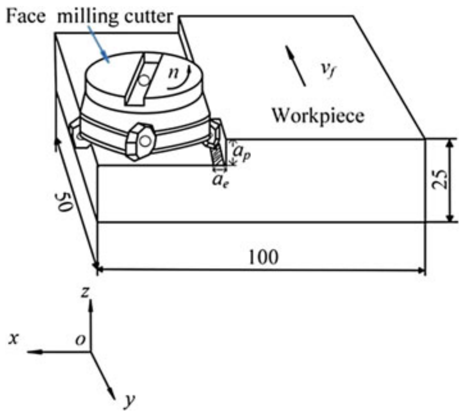

Fig. 2 Schematic of milling process

Table 1 Design of experiments by CCD

Level	1	2	3	4	5
v_c (m/min)	77.5	105.0	132.5	160.0	187.5
f_z (mm/z)	0.13	0.25	0.38	0.50	0.63
a_p (mm)	0.2	0.9	1.6	2.3	3.0
a_e (mm)	0.05	0.95	1.85	2.75	3.65

power are 15, 3.8, 3.8 and 3.8 kW respectively. During the face milling experiments, the power consumption of each electric motor was measured separately. Down milling along the *Y* axis was used to remove the materials (Fig. 2).

3.2 Design of Face Milling Experiments

In the present experiment, RSM was used for analyzing the effect of simultaneous variations of four cutting parameters (v_c, f_z, a_p and a_e) on energy consumption. Based on CCD, a total of 27 experiments (designed by Table 1) with 5 levels for each of the 4 factors were carried out. The optimization was done by the Design-Expert software, which combines experimental design, data analysis, visual model output and optimization of results. Finally, a feasible combination of v_c, f_z, a_p and a_e can be acquired, which satisfies the minimum energy criterion. The formula used for the regression of the experimental data is quadratic and can be expressed by Eq. (5).

$$Y = \sum_{i=1}^{n} \sum_{j=1}^{n} a_{ij} x_i x_j + \sum_{i=1}^{n} b_i x_i + c \quad (5)$$

3.3 Power Analyzing System

Power consumptions of four specific motors were measured by a power analyzing system (showed in Figs. 3 and 4), which was built up with a NI-9220 data acquisition card installed in a NI-cDAQ 9174 4-slot USB chassis. Each of the four electric motor's working power was measured by a voltage sensor (LV25-P) and a current sensor (LA55-P). Figure 4 showed the principle of the power analyzing system, while Fig. 3 visually showed how every part of experimental equipment was connected.

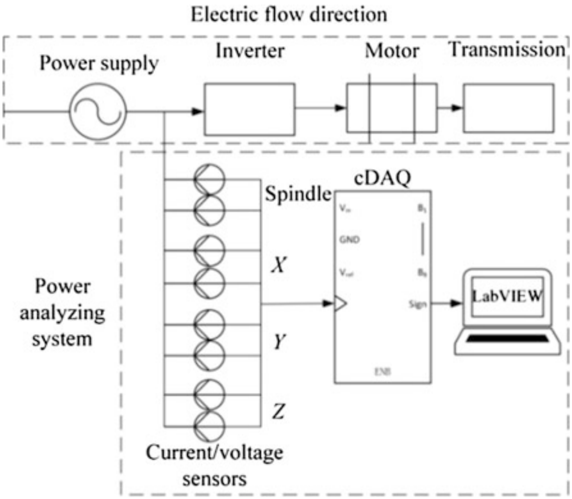

Fig. 3 Schematic of the monitoring system

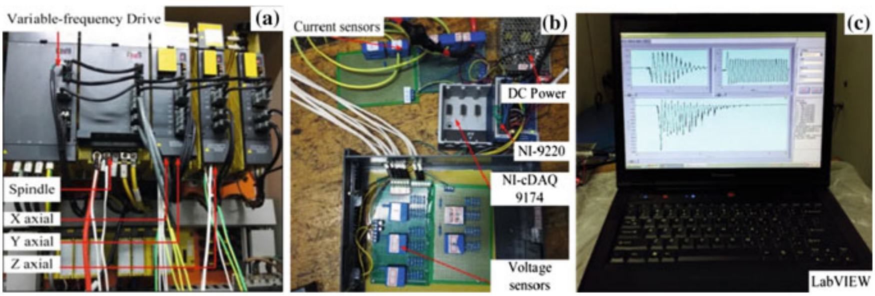

Fig. 4 Physical diagram of power analyzing system

4 Results and Discussions

4.1 Results and Second Order RSM Model Prediction Model Optimization

In the experiment, line voltage U_L and line current I_L were measured to get the motor power of each phase P_L. Then the power P of each motor can be calculated from Eq. (6),

$$P = \sqrt{3} U_L I_L \cos \varphi \tag{6}$$

where φ is the power factor with the value of 0.8. Form the results, it is obvious that P_M and P_Y are much higher than that of P_X and P_Z. But the Z axial motor's power was up to 2200 W at the time of starting, that's because the cutter was far away from the workpiece and closing speed reached 3000 m/min. Therefore, P_M and P_Y are the objectives to be optimized combined with surface roughness Ra, which was measured by an optical profiler Veeco-NT9300.

In the process of optimization, the responses do not have equal importance. The most important response are P_M and P_Y, followed by the surface roughness Ra. The free variables of each experimental factor and power consumption were transformed to the matrix form. The relationship between the power consumption and cutting parameters was established through the least square method. The final mathematical models of P_M and P_Y are given below:

$$\begin{aligned} P_M = & -22.07v_c - 3515.94f_z - 1378.73a_p + 1513.92a_e + 22.8v_c f_z - 8.357v_c a_e \\ & + 1610.9f_z a_p - 585.1f_z a_e + 157.4a_p a_e + 0.11v_c^2 + 260.9a_p^2 \end{aligned} \tag{7}$$

$$\begin{aligned} P_Y = & \; 13.15v_c - 370.05f_z + 53.32a_p + 485.34a_e - 1.84v_c a_e \\ & - 324.14f_z a_e + 97.49f_z^2 \end{aligned} \tag{8}$$

The experiments for significance of the regression and individual model coefficients were performed to verify the goodness of fit for the obtained model. The normal probability plots of the residuals vs. the predicted response for the power consumption are plotted in Figs. 5 and 6. The data closely follows the straight line. The null hypothesis is that the data distribution law is normal and the alternative hypothesis is that it is abnormal. When the P-value is greater than 0.05 (level of significance), the null hypothesis can't be rejected.

The results of analysis of variance (ANOVA) are listed in Tables 2 and 3. In which, the sum of squares is used to estimate the square of deviation from the grand mean. F-value is an index used to check the adequacy of the model in which calculated value of F should be greater than the F-table value. Table 2 shows that $R^2 = 0.853$, which indicated that satisfaction of Eq. (7) was 85.3 % and $R^2 = 0.853$

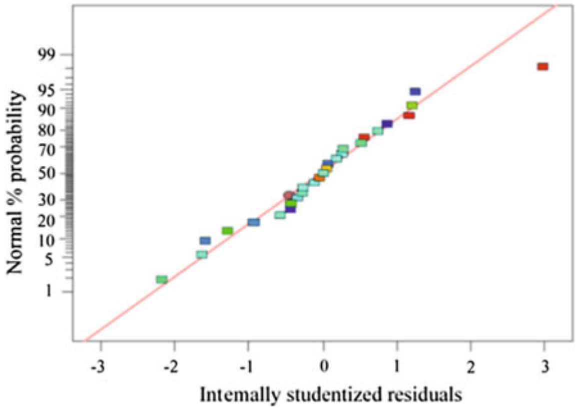

Fig. 5 Residual analysis result (Eq. 7)

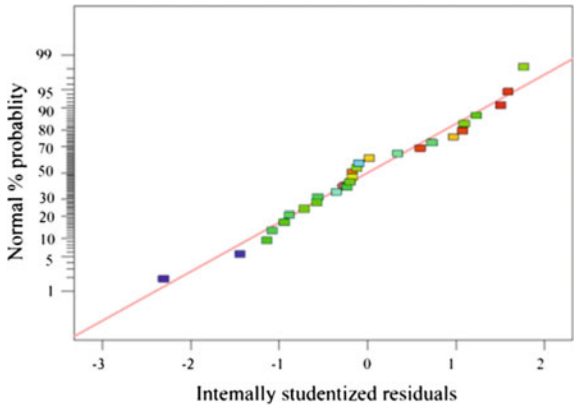

Fig. 6 Residual analysis result (Eq. 8)

Table 2 ANOVA for response surface quadratic model of Eq. (7)

Source	Sum_s	df	Mean_s	F	Prob > F	Significance	R^2
Model	6.54E+006	14	4.67E+005	4.98	0.0042	****	0.853
v_c	2863.399	1	2863.399	0.03	0.8643	–	
f_z	15509.45	1	15509.45	0.17	0.6917	–	
a_p	1659501	1	1659501	17.66	0.0012	*****	
a_e	2962703	1	2962703	31.54	0.0001	*****	
$v_c \times a_e$	684479.1	1	684479.1	7.29	0.0193	***	
$f_z \times a_p$	317886.8	1	317886.8	3.38	0.0907	**	
a_p^2	348670.8	1	348670.8	3.71	0.0781	**	

Table 3 ANOVA for response surface quadratic model of Eq. (8)

Source	Sum_s	df	Mean_s	F	Prob > F	Significance	R^2
Model	1.14E+005	10	11430.51	1.09	0.0056	*****	0.911
v_c	38491.25	1	38491.25	3.66	0.0238	***	
f_z	4377.78	1	4377.78	0.42	0.5280	–	
a_p	220.10	1	220.10	0.02	0.0068	****	
a_e	1739.10	1	1739.10	0.17	0.6897	–	
$v_c \times a_e$	33042.15	1	33042.15	3.14	0.0954	**	
f_z^2	38491.25	1	38491.25	3.66	0.0138	***	

in Table 3. The factors of a_p, a_e, and $v_c \times a_e$ were much more significant than others. The interaction of $f_z \times a_p$ had some effect on spindle power consumption. Table 2 shows "Lack of Fit F-value" of 23.69 implies Lack of Fit is significant. There is only a 4.12 % chance that a "Lack of Fit F-value" this large could occur due to noise. Table 3 shows "Lack of Fit F-value" of 0.81 implies "Lack of Fit" is not significant relative to the pure error. There is a 67.94 % chance that a "Lack of Fit F-value" this large could occur due to noise. From the above analysis, it has been asserted that the developed Eqs. (7) and (8) are well within the limits and can be used for the prediction of responses P_M and P_Y.

4.2 Parameters Optimization Based on RSM

Cutting parameters of v_c, f_z, a_p and a_e are the major milling parameters that are considered in these experiments for optimizing the power consumption. In this work, the multiple performance optimization of milling parameters is carried out using RSM based on desirability function approach. The optimal goal sets and limits and the importance of the factors are presented in Table 4.

In desirability-based approach, different best solutions are obtained and the solution with high desirability is preferred. The solutions are sorted with the most

Table 4 Goals set and limits used for optimization

Factors and responses	Goal	Min.	Max.	Lower	Upper	Importance
v_c	Is in range	105	160	1	1	3
f_z	Is in range	0.25	0.5	1	1	3
a_p	Is in range	0.9	2.3	1	1	3
a_e	Is in range	0.95	2.75	1	1	3
P_M	Minimize	3452	5295	1	2	3
P_Y	Minimize	591	980	1	2	3
Ra	Minimize	500	2000	1	1	3

Table 5 Global solutions for optimization

No.	v_c (m/min)	f_z (mm/z)	a_p (mm)	a_e (mm)	P_M (W)	P_Y (W)	Ra (nm)	Desirability
1	105.02	0.42	0.90	0.95	3452.96	702.585	303.94	0.897
2	105.00	0.42	0.91	0.95	3452.96	702.744	306.00	0.897
3	105.13	0.42	0.90	0.95	3446.55	703.038	309.38	0.896
4	105.00	0.42	0.90	0.96	3452.95	702.952	311.83	0.896

desirable first (Table 5). For example, the input factors are set at range, thus preventing extrapolation. From the analysis of the results, a group of optimal parameters obtained for machining is: v_c of 105.02 m/min, f_z of 0.42 mm/tooth, a_p of 0.90 mm, and a_e of 0.95 mm which could result in a minimum spindle power of 3452.96 W and Y axial power of 702.585 W, while surface roughness is insured with the value of 303.94 nm.

The 3D surface response figure visually showed the effects of the cutting parameters on responses. Interactions of a_p and a_e on spindle power is presented in Fig. 7, which shows that the increase of a_e and a_p increases the desirability and vice versa. In this condition, f_z and v_c are constant: f_z = 0.38 mm/tooth, v_c = 132.50 m/min. The graph is corresponding with the ANOVA results in Table 2. Thus, the power consumption is better at lower cutting speed and axial depth of cut. Interactions of v_c and a_p on Y axial power is presented in Fig. 8, which clearly displays that the Y axial power increases with increase in the effect of a_p and v_c. Results indicated that P_Y becomes lower while the a_p and v_c are all at a higher value. The graph is corresponding with the ANOVA results in Table 3. Thus, the power consumption is better at lower cutting speed and depth of cutting.

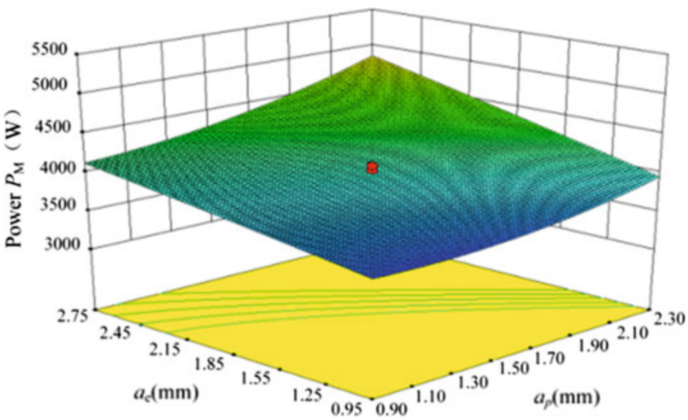

Fig. 7 3D plot of interaction of $a_p \times a_e$ on P_M

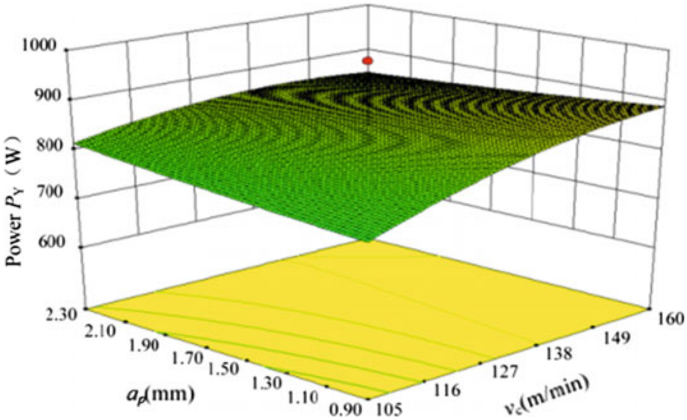

Fig. 8 3D plot of interaction of $v_c \times a_p$ on P_Y

Interaction of $f_z \times a_e$ on Ra is presented in Fig. 9, similarly influence of $a_p \times a_e$ on Ra in Fig. 10, which clearly displays that f_z, a_p, and a_e have an even greater impact on Ra. Dividing the total power consumption into four axial powers makes it easier to determine the optimal objection and simplifies the analysis process.

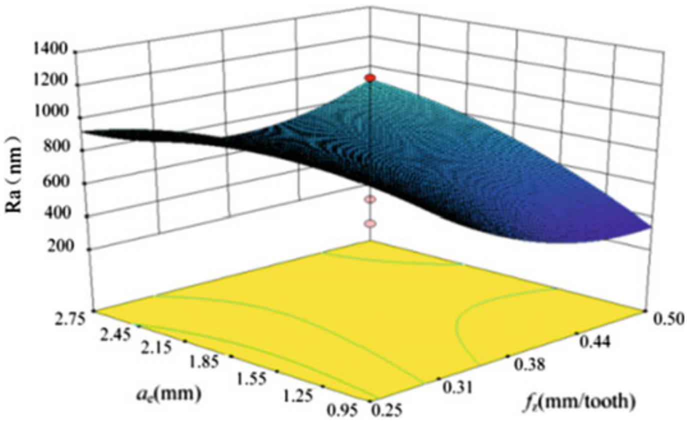

Fig. 9 3D plot of interaction of $f_z \times a_e$ on Ra

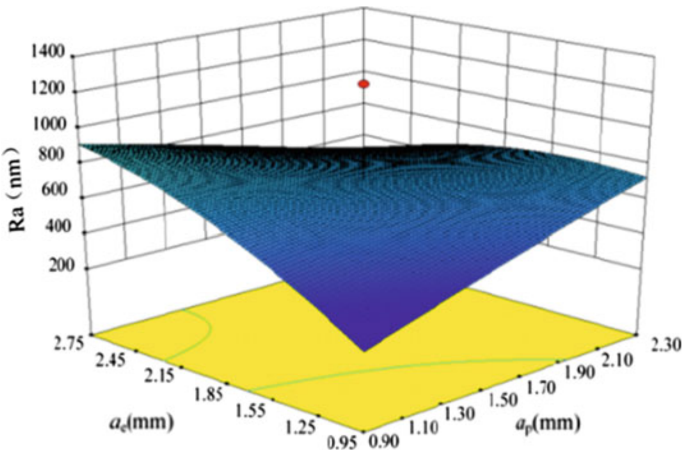

Fig. 10 3D plot of interaction of $a_p \times a_e$ on Ra

5 Conclusions

In this paper, the application of RSM for modeling the influence of cutting parameters on the power consumption of a face milling process is presented. Quadratic mathematical models based on RSM are developed using the results of experiment. Parameters of v_c, f_z, a_e and a_p as the major influence of the power consumption are considered to optimize the power efficiency during machining process. The following conclusions are drawn from the present investigation.

(1) The liner factors a_p, a_e, quadratic factor a_p^2 and the interactive factor $v_c \times a_e$ factors that can affect the spindle power. The significant factor on spindle power P_M is a_e.
(2) The liner factors v_c, a_p, quadratic factor f_z^2 and the interactive factor $v_c \times a_e$ factors that can affect the Y axial power. The significant factor on Y axial power P_Y is a_p.
(3) The optimal combination of cutting parameters are 105.02 m/min, 0.42 mm/tooth, 0.90 mm, 0.95 mm for v_c, f_z, a_p and a_e, which realized low power consumption and the surface roughness is insured.

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Innovative Active Cross-Linking Agents for Sustainable Leather Manufacturing

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Abstract For the first time New Active Cross-Linking agents (ACL) have been tested to process hides, demonstrating the possibility to produce good quality leather with a highly sustainable protocol. A comparison is made between ACL, chrome and other tanning agents commonly employed by the Leather Industry. In particular, ACL have been demonstrated to be the first tanning agents which leave no trace inside the skin producing totally non toxic tanned leather.

Keywords Leather · Cross-linking · Manufacturing industry · Sustainable production

1 Introduction

Sustainability has become an important issue in all spheres of life, focusing on the safeguard of people's life, environmental protection and natural resources exploitation. Companies around the world are showing increasing interest in environmentally friendly manufacturing [1].

The leather industry is a world-wide leading market concerning the processing of skin or hide of animals, which poses important quests regarding the environmental sustainability of the industrial process and waste management.

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Currently, Asia and in particular China is the world leader in leather production, along with India and Hong Kong. However, according to market overviews, Italy leads both the garment and the fashion industries surpassing both Asia and South America [2, 3].

According to 2013 Euroleather's report the turnover of the European tanning industry was estimated to be 7.8 billion Euros, corresponding to a production of 224 million m^2 of finished leather a year. Only in Italy in 2011 the total amount of chemical products used by tanning industries was equivalent to 47 million tons/year (ca. 0.4 kg/kg of leather produced). Of this amount 31 % are products containing substances classified as hazardous, according to European standard (DIR 67/548 CEE).

The European production is responsible for 17 % of the worldwide leather market. In 2013 according to UNIC (Italian National Union of Tanning Industries), Italy has covered 62 % of the European production, 60 % of which was processed by the Tannery District of Arzignano (TDA) and 30 % by Santa Croce sull'Arno (SCA) corresponding to an annual turnover of 4.9 billion euro/year.

Generally, European tanneries are companies of small to medium size and are specialized in the production of all kinds of leather for different goods such as footwear, garment, furniture, automotive (Table 1). The consequent flexibility, adaptability and the quick response to demand constitutes one of the industry's most important assets.

Nowadays, the average of bovine slaughtered Worldwide every year is roughly 300 million, corresponding to 15 million tons of hides. The leather industry transforms this waste into a valuable secondary material.

Nonetheless, leather manufacturing is water, energy and waste intensive and the tanning of hides is listed by the European Directive 96/61EC as an activity for

Table 1 European leather market in 2009

2009	Number of employers	Companies	Exports (%)	Production (1.000 m^2)	
				Bovine	Shep/Goat
France	1.529	53	33	2.663	2.306
Germany	1.925	18	60	7.000	450
Italy	16.717	1.378	68	96.921	29.295
Netherlands	325	5	71	4.000	–
Portugal	1.980	63	31	–	–
Spain	1.689	118	45	14.414	7.686
Sweden	260	4	90	1.100	30
UK	1.000	23	70	5.000	1.500
Romania(est)	900	15	–	300	1.250
Bulgaria	190	17	90	55	176
Norway	78	2	–	–	–
Total	25.613	1.633		131.453	42.693

which integrated prevention and control of pollution has to be achieved. Tannery effluents, if not properly treated, can cause serious damage to soil and water bodies.

Environmental concern clearly emerges from the European IPPC Bureau report 2013: at present over 85 % of the world leather production is chrome tanned and only 20–25 % in weight of raw bovine hides treated are transformed in final leather goods [4].

For 1000 kg of hides processed, only 250–300 kg of leather are produced, requiring 500 kg of chemical substances, 50 m^3 of fresh water and generating ca. 600 kg of solid waste, with a production of chrome containing solid waste of ca. 400.000 ton/year in Europe.

Most of the steps of in tanneries are performed in water. Consequently, waste water is one of the major concerns in tanneries. The characteristics of untreated waste water are a high chemical and biochemical oxygen demand, and a high salt and process chemical content.

The use of chrome poses serious environmental and health problems, due to the formation of carcinogenic Cr (VI) in the finished articles and in the slurries, pushing the most important fashion groups and the manufacturers to find innovative solutions.

Cleaner, high exhaustion chrome tanning technologies exist and are used industrially today to reduce chromium in waste water, nevertheless they are inadequate to eliminate completely chrome from water effluents [4, 5].

The substitution of chromium tanning agents has been limited until today; no valid alternative has yet been found to the use of Cr(III) salts due its ease of use, low cost, high quality and stability of the tanned leather, and the characteristic “hand” imparted to the finished product.

Currently, the main alternatives used industrially to tan leather (synthetic, natural tannins or aldehydes) impart physical and mechanical characteristics significantly lower than Chrome, without, however, solving the problem of health for the consumer and the environment impact since from this leather formaldehyde (carcinogen) and phenol (cytotoxic) can be released [6]. Formaldehyde, employed for the production of many synthetic tannins, will be banned from use in January 2016 for its assessed carcinogenic activity, making the quest for a new tanning alternative to chrome even more urgent.

The work hereafter reported will highlight the general advantages of an innovative and revolutionary class of Tanning Agents referred to as ACL from “active cross-linking” agents which could become a viable alternative to chrome in the future.

2 ACL Leather Manufacturing

Before illustrating the new ACL protocol it is important to give a general and schematic description of hides processing from the moment they arrive in the industry up to the tanning phase.

Scheme 1 Simplified scheme of the tanning process

Leather manufacturing may comprise up to 70 steps. The major processes are curing, soaking, flesh and hair removal, scudding, deliming, tanning, dyeing, rolling and finishing [6]. In the following the focus will be on the tanning step. The process, albeit its complexity, is very flexible and adaptable to different raw materials and to the final products wanted. In Scheme 1 are reported the first steps of the manufacturing process from soaking to tanning.

In the first step of the process (soaking) the animal skins are soaked with water in the presence of additives in order to remove the excess of salt, blood, etc. and restore a suitable water content inside the hides [7]. In the second step (liming, dehearing) the soaked skins are treated with an alkali ($Ca(OH)_2$) and sulfide solution (Na_2S) to facilitate hair removal and eliminate unwanted substances (non-structured proteins, fats, hyaluronic acid, etc.) [8]. The hide is now mainly constituted by collagen which is chemically modified and swells, leaving a more opened structure. Adhering flesh and subcutaneous tissue are mechanically cut off by fleshing. In the deliming and bating step (enzyme digestion) the skin structure is further opened up. Now hides need to be prepared for the tanning step by pickling; this specific step differs according to the specific tanning agent employed. All industrial protocols employed today require pickling.

Pickling is an acidic treatment carried out with mixtures of week and strong acids (formic and sulphuric acid are the most used) in the presence of sodium chloride, added to prevent a dangerous acid swelling of the pelt [9, 10]. According to the specific tanning agent employed the pH may be higher or lower in a range between $2.5 < pH < 4.5$. For historical reasons, all the preparative stages before the proper tanning step are collectively called beamhouse.

With the tanning process the skin is chemically stabilized and is converted into an imputrescible material due to the formation of interactions, bonds between the tanning agent and the collagen. The stability of the leather obtained after the tanning process can be ascribed to the chemical bonds formed between the collagen fibers of the hide and the tanning agent. Differential Scanning Calorimetry (DSC) is a widely used technique to evaluate the thermal stability of collagen after treatment, which is correlated to the cross-linking density within the collagen matrix. In particular, the DSC analysis of collagen typically shows a characteristic gelatinization temperature (Tg), originated by the transition from crystalline phase (triple helices) into amorphous random coils due to the breaking of inter-chain bonds [11].

The studies carried out by the group in the last years concern the innovative application of a class of chemical organic molecules used as activating cross-linking agents (ACL), with the aim to develop the know-how for their production and use, in manufacturing industry (pending patent).

In particular, the idea takes birth from an intuition which transposes a pharmaceutical protocol to large scale manufacturing industry, for the production of leather but also other applications are under study for the production of preservative-packaging, antimicrobial fabrics, high fixation dyes, etc. The great potential of these molecules (commercially available and of new formulation) is embedded in their multiple applications. At present these compounds have limited applications, except in pharmaceutical and biomedical engineering industry. These activators are able to link together different molecules with a mechanism "lock and key".

As for leather tanning their activity mimics the one of chrome salts since very strong bonds and cross-linking is formed implementing the stability of the collagen matrix, avoiding degradation in time.

The fundamental and unprecedented difference between all conventional tanning agents and ACL is that the latter act as "catalysts" or "enzymes", are not retained in the leather after tanning. They stabilize the collagen structure, increase the Tg, and leave no trace giving tanned leather which is devoid chemicals and is thus non-toxic.

At present, it is commonly accepted that a tanning agent is such if during tanning it is retained within the collagen matrix. ACL refuted this definition showing that it is possible to tan hides without the need of any chemical remaining permanently bonded to the skin. This is due to the ability of ACL to react functional groups already present in collagen, creating a level of cross-linking, stabilization adequate and comparable with that obtained with chrome.

ACL overcome one of the most critical aspects of all alternative tanning systems known today which give leather of lower quality, applicability, price, etc. to chrome leather. ACL are the first real alternative to chrome salts verified to date, as will be further explained below.

ACL is representative of a class of organic compounds, which can be easily modified and is under study in order to obtain libraries of molecules, having different performance which can be optimized as a function of the specific type of leather produced (footwear, leather goods, garments, etc.).

Although one ACL is commercially available at very high prices and has been tested, it has been verified that an innovative class of ACL can be produced with optimized characteristics and at competitive prices, especially devised for the leather industry (pending patent).

Hides to be treated with ACL protocol may be processed according to standard industrial protocols which is actually simplified with reduction in chemical, water and energy consumption. In fact, ACL do not require pickling and basification since they have maximum reactivity towards hides at neutral pH and high quality leather samples have been achieved after only 4 h (compared to 24 h with chrome) with 5 % in weight of tanning agent without any modification on the equipment employed. This characteristic allows to reduce the consumption of chemical products (acids, bases, NaCl), water and energy compared to chrome tanning.

Another important consequence of the non-toxic nature of the tanned leather, is the possibility to recover and recycle ACL tanned organic wastes for the production of high value products such as gelatin and liquid collagen for pharmaceuticals, nutraceutics, pets food, etc.

Chrome tanned scraps are now collected by specialized industries which, after a multistep purification process required to separate chrome from the organic waste, transform the recovered collagen into fertilizers for agriculture. ACL scraps can be processed devoid purification and ideally none of these wastes will be sent to landfill.

Tests were carried out both on powder collagen and on hides at different temperatures, pH, concentration, etc. The effect of the tanning by ACL is determined by Differential Scanning Calorimetry (DSC) which measures the temperature at which a material is subject to phase transition; in the case of collagen it measures the decomposition, gelatinization temperature (Tg); higher Tg give more stable products in time. Chromium salts give the highest Tg > 100 °C known today, while all other tanning agents give values around 75–78 °C, with a load of reactants which is often around 25–30 % in weight/weight of leather processed. The possibility to achieve Tg > 80 °C seams a limiting value of these technology and would constitute a great advantage in terms of collagen stability.

All newly devised ACL tested give Tg > 82–85 °C, and maximum 5 % in weight of reagent is required.

3 Conclusions

In conclusion in this paper we have given a brief overview of some of the most relevant problems inherent with leather manufacturing. In this panorama ACL technology stems as a very promising alternative to tanning agents employed today with significant advantages, such as:

- ACL reagents have been demonstrated to be efficient tanning agents able to tan hides giving characteristics comparable to chrome leather;
- ACL tan without leaving any trace in the final tanned leather which is thus non-toxic;
- No chrome is required for tanning. We estimate that if 10 % of the European market where to adopt this technology 400 ton/year of chrome will be substituted by ACL with a significant reduction in toxic waste disposal both liquid and solid.
- Reduction in disposal costs of leather scraps: at present Industries pay over 110 €/ton to specialized companies which reuse part of the material for fertilizers. These costs will be reduced or avoided when ACL scraps will be available for the production of high value end products.

– Studies are in progress to test ACL waste water treatment with conventional purification systems. So far it has been demonstrated that ACL are biocompatible with bacteria commonly employed for waste digestion.

It is to be stressed that although at present the main drawback to the use of ACL is posed by their price and availability, in the near future they will be present on the market at competitive prices thanks to the new synthetic protocol devised by us (pending patent).

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An Approach to Electricity Monitoring and Targeting (M&T) in Irish Precision Engineering SMEs

John Cosgrove, Frank Doyle, Frances Hardiman and Gerard O'Farrell

Abstract Energy management in small to medium enterprises (SMEs) remains undeveloped due to competing priorities and a lack of specialist knowledge. However considerable savings can be demonstrated where companies take the time to investigate their energy use and the specific production drivers that influence it. Savings of over 20 % can be achieved through changes to operational and behavioural practice. Additional benefits, such as improved production tracking and improved maintenance, can been seen which add to the value in undertaking an energy monitoring and targeting (M&T) plan. The method described involve the analysis of overall energy use from utility bills and the visualisation of power profiles to aid in understanding the drivers of energy consumption. The monitoring of specific machines in production highlights the significant consumption of electricity during non-productive times. The development of specific energy performance indicators (EnPIs) are described for product variations which can be useful in tendering for business and selecting optimum production pathways. The approach is illustrated with data from a case study of a precision engineering SME based in Limerick, Ireland.

Keywords Energy efficiency in industry · Production smes · Energy performance indicators

1 Energy

According to the World Energy Outlook Report (WEOR), [1] Manufacturing is responsible for 40 % of electricity consumption in Europe. The report states that the industry sector is very complex, and a detailed understanding of the various processes or product types is necessary to monitor energy efficiency.

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Even with the energy efficiency initiatives that are underway it is estimated that energy consumption in industry will rise by another 20 % between 2012 and 2020 [ibid]. Previous research [2] has estimated that only approximately 40 % of the potential for improving the efficiency of energy use in industry is exploited. The barriers to energy efficiency include the lack of visibility, low awareness, limited know-how and fragmentation of energy consumption.

1.1 Sustainable Manufacturing

The smart sustainable factory of the future [3] will be one where there is full integration between the production activity and the associated energy used and where the operation of the factory can be optimised around its energy and ecological impact. Energy efficiency in industry is the relationship between production output and energy input. A study [4] concluded that manufacturing industry can improve its energy efficiency by up to 26 %, while reducing the sector's CO_2 emissions by up to 32 %, based on proven technology. In Denmark, [5] showed that enterprises stand to gain by saving up to 30 % of their annual energy use, and increasing their productivity, through better energy management. According to [6] energy management and behavioural changes can achieve up to half of the remaining energy efficiency potential in industry.

Manufacturers who participated in energy efficiency programmes also experienced significant additional cost savings [7]. These Non-Energy Benefit (NEBs) include; improved production, cleaner environments, improved morale and more reliable operation. The search for energy efficiency has been shown [8] to also lead to productivity improvements. The uptake of industrial energy efficiency projects has been shown to result in lower maintenance costs and replacement costs of related components [9]. Research by the IEA [10] has shown that if NEBs are included, the true value of the energy efficiency projects might be up to 2.5 times higher than if looking at the energy efficiency improvements alone.

The detailed breakdown of energy consumption within various processes is not well understood [11]. The main reasons given [12] for not managing energy is lack of time, lack of resources, lack of knowledge and a primary focus on production.

1.2 Energy Usage in Production Machines

In one case study [13] the effective energy used to directly make the product in a metal processing factory was analysed as 48 % of the total energy consumption and this was referred to as an efficient production process. According to [14] a common characteristic of almost all manufacturing processes is that even when the machine is idle, it is consuming more than 50 % of its maximum power. With knowledge of the direct and indirect energy flows and their relationship to production activities it is possible to identify [15] the auxiliary (non-value added) energy within production where there may be significant potential for energy reduction. A study [16] showed that one of the main energy losses in the factory relates to production machine idling. For the monitored machining line, idling accounted for 23 % of the lines annual energy consumption. The report states that the idling energy losses are usually caused by inefficient operation by line personal.

2 Methodology

The proposed approach extends this methodology described by [17] to take into account the lack of existing data (energy and production) available in a typical SME.

2.1 Overall Electricity Consumption

As a rule, Manufacturing SMEs have limited metering of electricity, often just the main incoming utility meter. Limited electricity data may be drawn from utility bills which typically aggregate the daily consumption and which may also give a break-down between day-rate and night-rate units. Graphically displaying the daily electricity consumption for the previous six months or year, as shown in Fig. 1, will give a picture of the monthly/weekly patterns of behaviour of the business. The graph clearly shows the summer and Christmas shut-down periods and the lower (but still significant) electricity consumption each weekend.

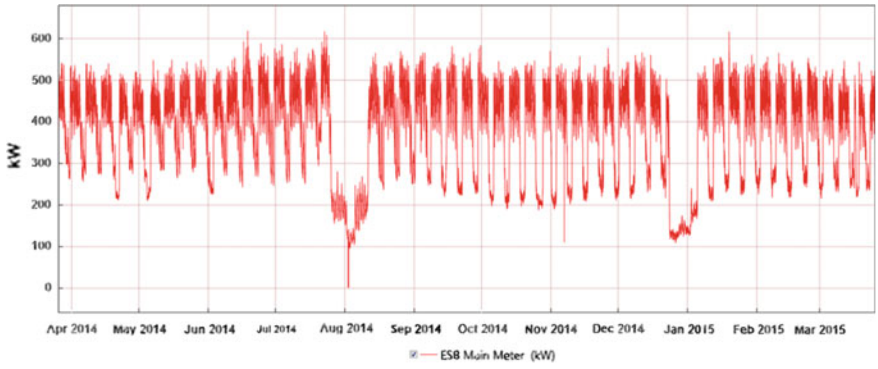

Fig. 1 Annual electricity profile of manufacturing facility

It is important for further analysis to establish estimates of the actual cost of electricity (and savings) in financial terms to the business and how it varies at different times of the day/week. This can be done through a historical analysis of the utility bills of the company over a suitable period of consistent tariff charges and structures (e.g. one to three months) and rolling up all the unit costs, distribution charges, transmission charges, levies, carbon taxes and other charges versus the number of kilo-watt hour (Whr) units consumed.

$$Electricity\_UnitCost = \frac{\sum_1^6 Monthly\ Cost\ of\ Electricity[€]}{\sum_1^6 Monthly\ Units\ of\ Electricity[kWhr]} \quad (1)$$

where the data is available this can be disaggregated into *Electricity_UnitCost_Daytime* and *Electricity_UnitCost_Nighttime* or into what-ever alternative tariff structure exists. The analysis will need to take into account any significant seasonal trends or major production shifts over the time period. If necessary a shorter or longer period may need to be analysed. For ongoing energy management in the business a monthly rolling analysis of the *Electricity_UnitCost* should be established as an Energy Performance Indicator (EnPI). In addition to consumption data, the utility bill also provides carbon emissions measures for the specific supplier, e.g. [18]. This data can be combined with the unit consumption data to provide the company with a metric for *Electricty_UnitCarbon*.

2.2 Power Profile

Where it is possible for the SME to access 15 min interval data from their utility providers online site, additional analysis methods become available. Combining online (and historical analysis) of electricity consumption with empirical knowledge of the production profile and history identifies high-level patterns and opportunities for further investigation. Where time-stamped data of overall electricity consumption is not available then the installation of a data-logger is necessary for sufficient weeks to establish the power profile.

One approach would be to aggregate energy consumption data against weekly working hour schedules, e.g. shift1, shift2, night-time, week-end. Whilst there may be variations from time-to-time an initial analysis against the scheduled productive and non-productive times does provide an estimate of the potential waste of electricity through idle running of equipment. This estimate is a useful means to gain the attention of the business owner/manager. For example, Fig. 2 shows the aggregated weekly electrical consumption profile for a manufacturing plant and indicates the scale of week-end electricity consumption (20 %) compared to known week-end production volumes (5 %), thus highlighting opportunities for savings.

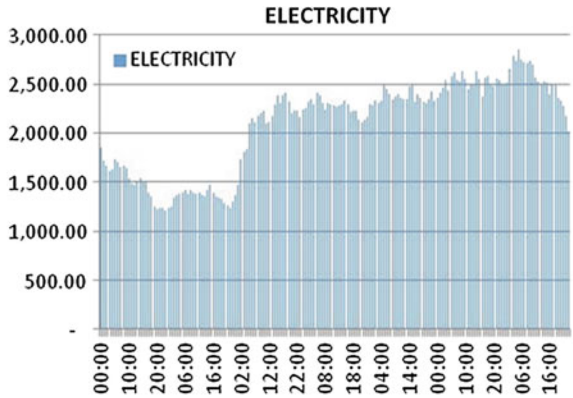

Fig. 2 Aggregated weekly power profile (kWhrs) for a manufacturing plant

Another approach, if suitable, is to carry out data-logging through a shut-down period such as Christmas, holiday weekend, etc. in order to establish a base-line of non-productive power consumption. For example, in the manufacturing plant illustrated in Fig. 3 the electricity consumption over the Christmas shut-down accounted for a waste of €1000 over six days. Assuming that the same idle-power consumption continues through-out all non-productive times in the year (Nights/Weekends), the waste accounts for 30 % of total electricity consumption.

For ongoing energy management a monthly rolling analysis of the *Electricity_Non-ProductiveConsumption* should be established as an Energy Performance Indicator (EnPI).

Another approach is to use detailed interval data to create a visualisation of the electricity consumption data using conditional formatting in Microsoft Excel. Figure 4 shows an extract from an electricity map spanning 5 weeks from the 1st June 2015 for a manufacturing plant. The rows represent calendar days and the columns are aggregated to 30 min data. Normally the full 24 h period is included, but in the diagram below an excerpt from 4:00 am to 5:00 pm is shown for clarity. The non-productive weekends (green rows all the way across) can be clearly seen as can the low levels of electricity use before 8:00 am (green area on the left). The first

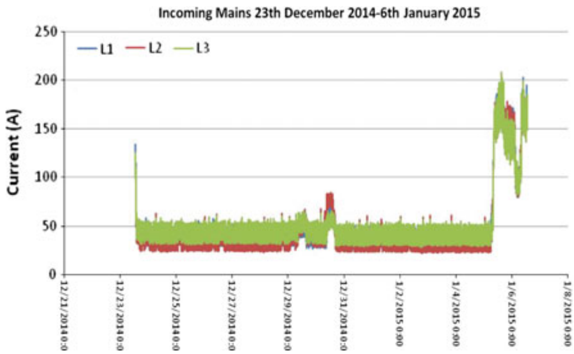

Fig. 3 Base-load through Christmas shut-down

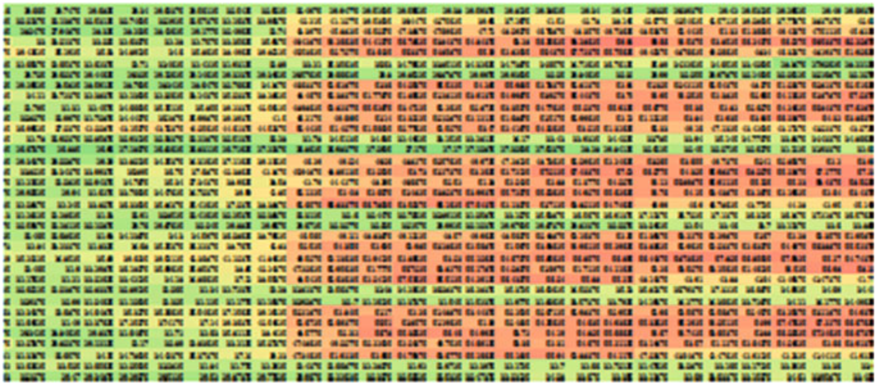

Fig. 4 'Heat Map' of electricity consumption

week is notable as June 1st was a bank holiday and there were 4 productive days that week with a noticeable difference in pattern—less electricity consumed on Tuesday and Wednesday and greater than average later in the week. This can be explained by a variation in client orders due to the holiday weekend. In conjunction with interview of the production personnel the profile peaks can be investigated to understand what activity in the factory drives the major periods of consumption. In addition, the availability of real-time production tracking data, machine-level data or other potential proxy data at the times of peak consumption should be identified.

2.3 Production Process Analysis

Based on the information from the steps above the significant production process steps and/or machines can be identified. Both the throughput (i.e. batch size) and the cycle time for each unit of manufacturing (i.e. cycle time/batch) should be analysed. Name-plate data and/or maintenance records should provide data on the rated power consumption of the machine. Where that is insufficient, temporary non-invasive metering and logging of representative power consumption should be carried out. From this information it is possible to analyse the auxiliary energy [11] or waste that occurs during productive time.

$$\begin{aligned} Electricity\_ValueAdd = {} & (\#\,ProductionUnits \times CycleTime) \\ & \times (Production\_AvgPower) \end{aligned} \tag{2}$$

Therefore, the auxiliary electricity consumption for a specific Machine is;

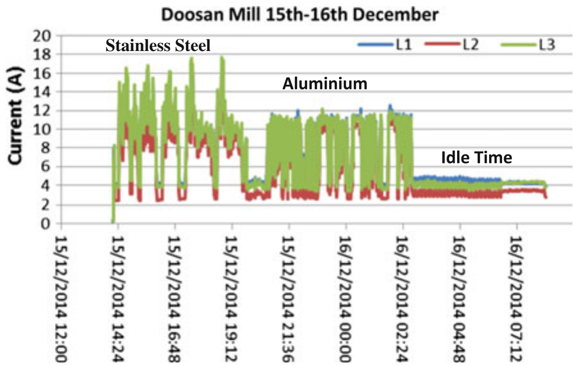

Fig. 5 Material profile variation on a machine

$$Electricity\_Aux\_MC1 = \sum_{0}^{t} Electricity\_Total - Electricity\_ValueAdd \quad (3)$$

This can be compared historically against past performance, set against a target to be achieved and used as a measure of comparison between machines carrying out the same function. Monitored over time, this metric also gives a clear measure of the machine loading or utilisation rate. Using the *Electricity_UnitCost* developed above, the potential savings that can be accrued over a time period (shift, week, month, etc.) by increasing the capacity loading or by turning off the machine during idle times can be calculated.

In addition, selecting a product type as the basis for analysis can provide specific energy performance indicators (kpis) which identify the embedded energy cost per production part. Figure 5 shows a comparison in machine electricity consumption for a job completed in steel versus one completed in aluminum. This is particularly useful for manufacturing SMEs where the knowledge of specific cost, for example, per kg of steel, would be useful in tendering for work and in selecting optimum production pathways.

3 Case Study

The use-case was a precision-engineering facility based in Ireland (Manufacturing SME1). The company employees over 40 skilled personnel and has been operating for 20 years. They primarily process parts in steel, aluminium and plastic for applications in the medical devices industry. The principle objective for the company was to quantify and determine the individual cost per part manufactured and the carbon impact of this energy usage. In addition they wished to increase their understanding of the factors that affect the sites energy consumption with a view towards reducing energy consumption and costs in production.

3.1 Overall Energy Patterns

Manufacturing SME1 operates 5 days a week with a day shift only. An analysis of their electricity bills from April 2014 to Jan 2015 was carried out, showing electricity consumption from the grid of 260,000 kWh. As the company operates mainly from 8:00 until 16:30, this is the period that has high energy use, however a significant energy use and cost are evident for non-productive times. The number of units consumed during the day and night periods were analysed together with the various costs itemised in the electricity bills to establish the actual monetary cost of a unit of electricity during the day and night periods. This provided the following metrics; (See Table 1).

Analysis of the electricity utility bills day and night values (two values per day) was carried out to identify the amount of energy used in productive and non-productive times. A baseline was established taking night time values and making the assumption that a similar amount of energy was being consumed during the evening after production from 16:30 at the day rate until 23:00 when the night rate begins, it can be estimated that at least **40 %** of the total energy usage is related to non-productive times giving a monetary value for potential savings of circa €23,000 per annum.

A significant amount of this energy is due to machines being left on with fans, heaters, components etc. running. From a shutdown periods over the Christmas holidays, the total electricity usage was as low as 125 kWh for a 24 h period. This compares to a minimum of 200 kWh for a 24 h period at weekends and bank holidays throughout the year. Thus, just stepping equipment at week-ends back to the level achieved during the shutdown could provide savings of 8000 kWh per annum.

3.2 Production Process Analysis

From the initial analysis a number of production machines were selected for further monitoring. The 3 phase supply to the Hi-Turner machine was monitored over a two week period in March 2015 as shown in Fig. 6. The production data for the parts produced were compared with the energy consumed. It can be seen that the machine was only productive for 3 days of this period and while it was in idle mode it consumed approximately 33 % of its full load usage.

From the production figures, 25 parts (Product A) were manufactured each day. Each part cost approximately €0.23 in electricity to manufacture on this machine with an associated carbon emission impact of 0.56 kg. It is calculated that the

Table 1 Energy performance indicators

Electricity_UnitCost_Daytime	€0.2195 per kWh
Electricity_UnitCost_Nighttime	€0.1652 per kWh

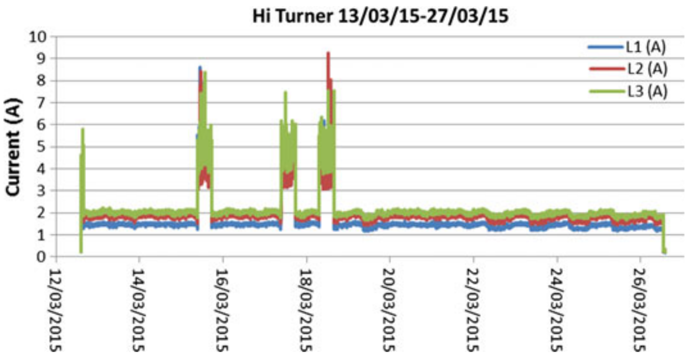

Fig. 6 Hi-Turner current profile

machine electricity cost approximately €5.80 for each production shift. While the machine was in the idle or waiting state, it cost €5.89 per day or €0.25 per hour in comparison with a productive cost of €0.64 per hour. Further investigation is necessary to verify that the machine can be fully isolated when not required without affecting production operations.

An Okuma Lathe was monitored for a two week period with the results shown in Fig. 7.

It can be seen that this machine was in operation for approximately 9 days from the measurement period of the 13th of March until the 27th March. During this period a significant level of electricity was consumed when the machine is in an idle or waiting state. In particular, there was an unusually high idle consumption overnight on the 27th March which does not correlate with production activity and may indicate that some machine maintenance is required. It was calculated that the

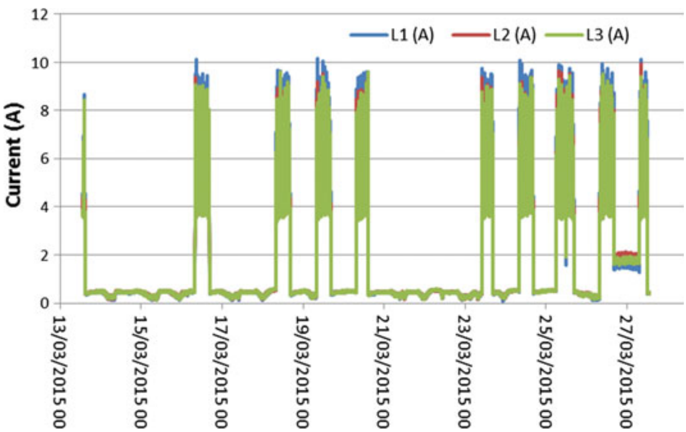

Fig. 7 Okuma current profile 13/03/15-27/03/15

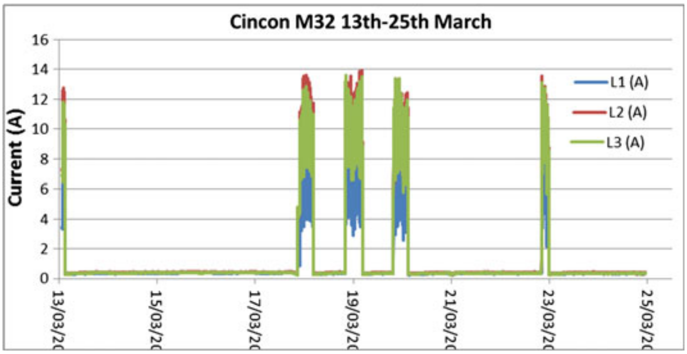

Fig. 8 Cincon M32 current profile

electrical costs of running this machine vary from approximately €6.13 to €7.81 for each shift of actual production.

For example; production figures for the 16th March show 16 parts (Product B) were manufactured. Thus each part cost approximately €0.53 to manufacture on this machine with a CO_2 emission of approximately 1.26 kg per part. Further investigation is necessary to verify that the machine can be fully isolated when not required without affecting production operations.

A Cincon Lathe (M32) was monitored for a two week period with the results shown in Fig. 8. Although the machine is not electrically isolated after production it is not consuming large amounts of energy (approx. €0.03 per hour).

Energy usage during production costs €0.97 per hour with each shift costing circa 21.1 kg in carbon emissions. Very limited savings can be achieved through isolation of the machine during non-productive times.

As well as the energy savings, the Facilities and Maintenance Manager for the factory has been particularly impressed by the useful information that can be gained through logging the electricity consumption on the machines, the potential for better understanding production operations and the ability to identify non-energy benefits such as improved production throughput. The company is investigating monitoring all its machines for energy and production purposes based on the opportunities identified in the case study.

4 Conclusions

Significant electricity and carbon emission savings can be achieved in precision engineering SMEs through behaviour and operational changes. The attention of SME business owners can be directed towards energy efficiency savings by presenting available electricity consumption data in graphical and visual forms that highlight the factory profile.

Approximate calculations of actual electricity unit costs and analysis of productive and non-productive times can be used to highlight and quantify potential electricity and carbon emissions savings that can be achieved through change in practice. In the use-case under study, potential savings of 40 % amounting to €23,000 per annum were shown to be available.

Developing a clear link between the temporal profile and efficiency of the energy consumption by a specific production machine can provide useful measures for costing and organising jobs. Detailed machine level monitoring clearly identified waste due to idle running. An example was shown where 33 % of total electricity consumption added no value. Metrics were discussed which if maintained on a continuous basis would provide simple tools in the better energy management of manufacturing in SMEs.

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Exploring the Scope of Industrial Symbiosis: Implications for Practitioners

Maria Holgado, Dai Morgan and Steve Evans

Abstract Industrial Symbiosis can help improve the overall efficiency of the industrial system. The positive impact of implementing symbiotic exchanges between companies would benefit their host region through increased job creation and reduced environmental stress, whilst the entities engaged could benefit from a combination of additional revenue streams and reduced costs. However, in spite of the potential benefits of IS, there remains an implementation gap, with practitioners failing to fully exploit the possibilities of IS. The objective of this article is to provide a review of the current state of IS research in order to unlock current gaps of knowledge and practice, and identify research opportunities which will help close the implementation gap. The final aim is to explore and understand the areas practitioners willing to engage with IS need to consider in order to operationalize IS in their network.

Keywords Industrial symbiosis · Geographic proximity · Manufacturing processes · Energy efficiency · Resource efficiency · Network · Eco-Industrial parks · Waste management

1 Introduction

Sustainability in manufacturing needs to be tackled from a holistic perspective [1]. Emerging as a construct drawn by observing and interpreting the behavior of industrial systems, Industrial Symbiosis (IS) can bring clear improvements at company level and also at network level. According WRAP [2] IS can help

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companies to reduce raw material consumption, carbon emissions and waste disposal costs while diverting waste from landfill and opening new business opportunities related to potential revenue streams from residues and by-products. IS can be considered a key element for the circular economy. Together with reuse, remanufacturing and recycling strategies, IS contributes to the creation of value through the exploitation of waste streams, emissions, and discarded products, in order to feed other products or production processes [3]. It also brings benefits from a social perspective. For example, at local and regional levels, IS can contribute to environmental improvements and new jobs creation [4].

Despite the claimed benefits of IS, its implementation remains challenging for practitioners implying a gap between theory and achievements in practice [5]. The objective of this article is to review concepts and dimensions associated with IS practice in order to unlock current gaps in knowledge and recognize research opportunities. The final aim is to understand which areas practitioners (i.e. any party who might be involved in the exploration or implementation of IS opportunities) need to consider and to explore how to develop support for those practitioners willing to engage with IS.

The next section introduces the emergence of IS as a concept, defining the scope of the inquiry. Subsequent sections concentrate on practical aspects identified from literature areas including IS, Industrial Ecology (IE) and Eco-Industrial Parks (EIP). We have searched the literature on the design, planning or implementation of IS for practitioner relevant insights. Key dimensions identified from the literature include: IS operationalization, geographic dispersion, network development and intermediaries. This is followed by a review of social aspects of IS. This article concludes with some final thoughts after a discussion on gaps and research opportunities related to the practical implementation of IS.

2 Origins and Definitions

IS as an idea was inspired by the example of Kalundborg, in Denmark where a complex network of material, water and energy exchanges between industrial actors and the local municipality emerged over a period of around 40 years [6]. It was identified as an example of interest in the early stages of the Industrial Ecology movement, and became inspiration for the development of eco-industrial parks in the USA in the 1990s. A number of definitions are offered by the literature however there is no definitive definition.

Ehrenfeld and Gertler [7] reflect on IS as a focus on industrial efficiency at the system level, measured at the scale of the system as a whole, rather than at the factory level. Thus, some of the companies, viewed independently, may appear to be inefficient, yet environmental performance can be superior in the overall group of companies. In 2000, Chertow positioned IS as a part of the emerging field of Industrial Ecology which “demands resolute attention to the flow of materials and energy through local, regional and global economies”. IS was described as "traditionally separate entities (engaged) in a collective approach to competitive advantage involving physical exchange of materials, energy, water" [8]. This description emphasized collaboration and geographical proximity as key factors in synergies, focusing, on the IE subset of flows operating at inter and intra firm levels.

Chertow later expanded on this view in 2007 [9], introducing the 3-2 heuristic[1] to aid the identification of symbiotic examples in practice. Lombardi and Laybourn [10], drawing on the experience of a UK based scheme funded by the government from landfill tax, frame IS as a tool for innovative green growth stating that "IS engages diverse organizations in a network to foster eco-innovation and long-term culture change" and explicitly diminishing the emphasis on proximity as a key determinant of IS.

3 Operationalizing Industrial Symbiosis

What does it mean in practice? IS related exchanges can occur as a one-off material waste exchange(s) or more continuous flows can be exchanged between different entities with certain geographic proximity [8]. IS opportunities occur at the level of an industrial process [10] and can therefore be realized by a single company or factory (intra-firm IS) or in partnership with other companies (inter-firm IS).

How does it come about? IS can emerge unprompted from the interactions between companies as serendipitous arrangements. Some attempts to plan IS include the design of industrial estates and eco-industrial parks [11, 5]. Paquin and Howard-Grenville [12] propose *Facilitated IS* as an intermediate arrangement between self-organized and planned IS. In facilitated IS symbiotic exchanges are enabled by a third party intermediary such as the National Industrial Symbiosis Programme (NISP) in UK which is the world's largest coordinating entity for by-product use between regional clusters [9, 10]. Facilitation and coordination could also be seen as part of the evolution of IS after its initial establishment in order to enhance the potential opportunities for collaboration [13].

Company size. The mode of engagement with IS may strongly depend on company size. Larger companies with multiple sites are more likely to engage in intra-firm IS [14]. Conversely, SMEs would be more likely to need collaboration with others in order to realize IS opportunities. IS opportunities for SMEs could additionally come from "mutualisation", i.e. for sharing or creating new waste management infrastructures, facilities and services between them [15]. This type of solution would tackle the issue of "whether there is sufficient flow of materials to make IS worthwhile" [8].

[1]I.e. that a minimum of 3 organizations (none of which is primarily involved in recycling as an industry) exchanging 2 resources as a minimum condition for symbiosis.

3.1 The Geographical Dispersion

Geographic proximity between entities was identified as an enabler of the advantageous exchange of resources among different industries, however, certain types of waste may have trading opportunities at local, regional, national or global level [8]. Waste with high market value and relatively cheap transport cost such as metal, electrical and electronic equipment, plastics, paper and oil are mostly collected from and delivered to longer distances [16], thus, being candidates for IS applications outside the local scope. Some authors argue that the adequate scale for IS is the region [17, 18] whilst others emphasize local collaboration and partnership [19]). Diversity and complementarity of local organizations has been highlighted as an important factor to create high-value collaborations [20]. The *local level* therefore seems to provide an appropriate scale of application for certain types of IS, especially when considering the deployment of EIP that will bring a series of companies with common or complementary needs together to the same geographic location.

At a *regional scale*, there is some evidence that EIPs look beyond their local area, expanding the exchanges outside their own boundaries [5]. Zamorano et al. [21] consider proximity between industrial parks in a region as a positive aspect that enables collaboration on waste management processes and systems as reaching economies of scale. Similar findings are reported by Ruiz Puente et al. [15], whilst NISP first attempts to find resource matches at a regional level.

Chen et al. [16] suggest that exchanges already occurring at regional level do not imply the need to realize the exchanges at this level for all types of waste. At *national level*, evidence has been found of inter-regional exchanges facilitated by national programs; NISP coordinates different regions to facilitate matches where local or regional options are not available. National programs for IS applications and for the deployment of EIP have been funded in several countries so far: UK, US, Sweden, China, Japan, Germany, Spain, Italy, Korea [15, 20, 22–25]. We have not found any *intercountry* application of IS in literature or practice so far.

4 The Network Perspective

The scope of IS network research to date focuses mainly on IS planning and design while coordination and management of IS networks are still little explored [13]. Cooperation is at the core of IS concept [10, 13]. IS itself implies a sense of cooperation and networking either when the resource exchange is done at factory/organization level or among different companies. Chertow's 3-2 heuristic [9] implies a network approach to IS, rather than a dyadic relationship between exchanging companies.

Inter-firm cooperation needs to be actively supported in order to keep the IS network running over time. An environment of trust can facilitate IS deployment, for example, reducing some related transaction costs: (i) search costs, related to the identification of opportunities for exchanges; (ii) negotiation costs, related to the agreement on the terms of the exchanges; (iii) enforcement costs, related to putting in effect the contract [13].

There are still few studies on IS network evolution and resilience over time. Some factors, such as the establishment of mutually beneficial transactions and a joint network vision during the planning process could assure long term commitment [26, 27] while others, such as the closure of any involved companies, an adverse reaction of local community or the global/national trends in particular sectors, can create disruption in the operation of the IS network and cause radical changes or even its decline [28]. Trade-offs regarding resilience and efficiency of IS networks have been studied. Resilience increases with the addition of different industries and redundant commodity exchanges [29] but decreases with interfirm dependency [30]. However, high-interfirm dependency increases the network's overall efficiency and reduces the risk of eco-efficiency losses.

4.1 The Role of Intermediaries

Third parties have been often involved in recycling and selling the recycled materials. IS can bring more trading opportunities for them [8]. Waste-solution providers and specialized waste companies have played a key role during the NISP implementation [4] and the selection of authorized waste management companies in EIPs is seen as a means to reach economies of scale [21]. Although they can play a key role in IS networks, the study done by Posch [27] revealed that recycling companies tend to establish transaction-based dyadic relations and lack a shared network identity, network culture and shared objectives.

Occasionally, by-products cannot be used directly as inputs in manufacturing processes and require treatment by intermediaries or "middleman" [13]. These intermediaries need to be included in the network management and coordination processes, thus, having an impact on supply chain structures and complexity. Indeed, waste collectors and processors are envisaged to have a critical role in supply chains including IS exchanges [31]. Their capabilities increase the opportunities within a given supply chain or network, to create closed loops systems. Similarly, the waste management companies could expand their scope and develop more capabilities to support new exchanges [4], thus, creating more potential value for the whole IS network.

5 The Social Aspects of Industrial Symbiosis

While economic and environmental motives, methods and benefits are mostly present in IS literature, the social dimension of IS has been frequently neglected, being addressed by limited research or industrial applications [27, 32, 33].

However, attention is increasing on the social side of IS exchanges and network development. From a stakeholder theory perspective [34], there are numerous entities or groups that affect or are affected by the IS. Apart from the companies directly involved in the exchanges, other relevant stakeholders include industrialists, regulation bodies, interests groups and consumers [27] as well as local communities, regions or countries as a whole [4, 13, 35]. Additionally, intermediaries for waste management and treatment are also new stakeholders which will influence strongly the value obtained out of the symbiotic exchanges. Cities, towns or residential communities nearby industrial settings can also participate in IS exchanges. New symbiotic exchanges can be generated by linking the management of municipal solid waste (MSW) with local industries [16, 36].

The interactions among companies within IS networks are attracting more and more interest in the research community. Social factors included in IS studies relate to institutional capacity, culture change, inter-firm learning, social embeddedness and social capital. Institutional capacity regards the "recurring interactions between a group of actors that expands in number and range over time" [37] enabling the development of the IS network. The long-term thinking required for IS implementation will bring changes into companies' culture. IS can foster long-term culture change, environmental innovations at local scale and promote inter-firm learning and knowledge generation [10, 20, 27]. Thus, a highly cooperative organizational culture within the industrial area would be expected to contribute to a successful IS implementation [38]. In this regard, cross-sectorial innovations as well as new research and technology development were interesting outputs of NISP, enabled by mutual learning and firm-specific knowledge sharing among companies [10].

The role of trust has been emphasized as an enabler of IS but there is still little understanding on the mechanisms for building trust and cooperation [33]. This is being addressed by studies on social embeddedness and social capital. The concept of embeddedness has been adapted from the field of sociology to IS in order to understand how social and cultural aspects influence decision-making during IS planning and implementation [33]. Within an IS context, the social capital concept refers to network connections and relationships in the companies participating in the exchanges [39]. The social capital of middle managers can be crucial for IS opportunity identification and development, especially in self-organizing IS settings [40]. The study done by Doménech and Davies [33] connects emotional ties in IS relationships to IS project examination approach and the reciprocity in the IS network. The presence of emotional ties would influence IS project evaluation as a more heuristic approach and a global perspective are taken rather than narrow economic calculations and would, moreover, improve reciprocity between companies in the network as well as knowledge transfer and cooperation.

6 Gaps and Research Opportunities for Industrial Symbiosis Implementation

Companies could see in IS an opportunity to extend their resource productivity [8] while transforming negative environmental externalities into positive environmental benefits [13]. However, practitioners need to be cautious as IS may not be the only or optimal mechanism to solve all energy and resource efficiency problems. IS opportunities should be compared to other possible improvement mechanisms in order to assess its viability and applicability and to find the most eco-efficient solution [20, 41]. For example, if disposal of waste is just a small percentage of operating costs or if there is not scarcity of resources in the area, IS may be less attractive [8]. The appropriateness of the solutions will be strongly influenced by contextual factors. These factors can be related to social, informational, technological, economic and political aspects that will conform a potentially enabling context for IS [42] as well as environmental factors that will influence the reliability and life span of the IS network [43]. There is then a need for further research on tools and methods that can support practitioners to identify, at early stages of ideation, the available opportunities for their waste streams and for their procurement activities from an IS viewpoint and to evaluate these opportunities against other possible strategies for efficiency improvements.

Government policies may influence a wide range of aspects when looking at IS networks [5, 22]. For example, waste management is still not a common concern for many top managers [27] and this may be inhibiting efforts devoted to IS development. Regulatory measures could support IS implementation and create higher awareness among companies' top management. Regulations that penalize lower waste hierarchy management levels and coordination programs to facilitate and assist companies during the IS opportunity identification stage are examples of possible positive government interventions [42]. Conversely, practice may be aided by the removal or amendment of legislation and regulation which inhibits IS, e.g. removing unnecessary bureaucracy and streamlining processes.

Thus, there is not a one-size-fits-all when planning and implementing IS as context specific characteristics will shape the scope and opportunities for IS in each individual case. These characteristics include but are not limited to; company size and production processes, geographical landscape and regional industrialization as well as country-specific trade regulations and policy. The high degree of characterization needed for the design of IS in different contexts means practitioners would benefit from support (e.g. tools and methods) developed specifically to address contextualization challenges for IS design and planning.

Last but not least, for IS to flourish in practice, all actors in a potential IS system need to derive value from the network. Understanding the benefits (both monetary and related to other forms of value) provided to all actors in the system will help create the levels of trust that will keep the IS system running. Especially in facilitated IS, once the facilitator has left the system, built trust and well-understood benefits could support the survival of the IS system. It appears therefore that reciprocity is a key principle for practitioners wishing to design and implement IS, with the reciprocal benefits of network participation potentially underpinning long term success of IS implementations.

7 Concluding Remarks

IS was established as a term of art within the field of IE, capturing a particular configuration of industry, found in Kalundborg Denmark, and typified by a complex web of resource exchanges. The definitions offered for IS vary but the broad identity is a network of actors who exchange resources which would previously have been wasted in some way. This recovery of latent value can occur within companies, between companies who are often (but not always) proximate, and who may be from previously unrelated industries. Thus, a symbiotic relationship is established between processes (in terms of resources) and companies (in terms of value) contributing to competitive advantage.

Implementation and active design of IS systems however has proved challenging in practice, with numerous failed or partially successful exercises noted in the literature and few successors or equals to the original inspirational example identified. Where success has been achieved in practice and documented it has often emerged in incremental fashion, developing over time and contributing to the overall business or network goals. In a notable example (NISP), facilitation of knowledgeable experts and a capacity for innovation has been identified as key factors in encouraging resource based exchanges.

Drawing on the metaphor of IS, we can see that companies are already engaged in a complex web of exchanges of resources and value which is the basis of the product and service delivery system which we rely on. The notion of IS specifically refers to the waste which arises as a by-product of that system. From a waste hierarchy perspective we might choose to reduce or eliminate the wastes before recycling and re-using them. However the latent value which is contained within the wastes should also be considered and evaluated as part of the business proposition. Indeed when viewed through an innovation lens, we might re-conceive the framing of IS as part of the core business search for competitive advantage.

This suggests that IS is something which emerges from latent value associated with surplus resources within an industrial network, which is exploited through innovation and cooperation. The implication of this being that it is necessary to treat waste not as a problem whose negative effects are to be minimized but as a resource from which maximum value can be extracted.

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Towards Reverse Logistics Archetypes to Stimulate Manufacturers' Usage of End of Life and End of Use Products

Serhan Alshammari and Peter Ball

Abstract There is an increasing need to recover value from products from their end of use and end of life phase as a result of issues of mitigating against resource scarcity, increasing legislation and emerging business models. Reverse logistics is a core process for recovery. There are economic and environmental drivers for such an activity. The challenge for industry is the absence of models to support the development of reverse logistics operations. This absence is both in practice and in the literature. Here we develop generic archetypes for the reverse logistics activity that capture the common structure and the main. The work has been developed through adopting supply chain structures in literature and interviews with industrial experts. The three main archetypes developed here are: low value extended producer responsibility, service parts logistics, and advanced industrial products recovery. The reverse logistics archetypes definition will help firms to identify their key drivers for their reverse logistics structure and help to plan the activities within this process.

Keywords Reverse logistics · Circular economy · Recovery · EPR

1 Introduction

Reverse logistics processes that support product value recovery serve the development of industrial systems both economically and environmentally sustainable [8]. In order to resolve the problem of environment pollution and realize sustainable development, the concepts of circular economy and reverse logistics are both very important. In essence, reverse logistics is the key to the circular economy, while the

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circular economy development will promote the development of reverse logistics [17]. Circular economy is the approach where we maximize the reuse of finite resources through changes in business structure of industrial systems in terms of design and eco-efficiency [10].

Firms find themselves hindered in the adoption of circular economy concepts through lack of definition of the type of reverse logistics that they have to in turn seek best practice. In order to understand the types of reverse logistics, we need to understand the reverse logistics drivers and factors that construct those types.

This paper provides a simple definition of reverse logistics archetypes that work as guides for understanding and planning reverse logistics. The structure is as follows: first we introduce the reverse logistics concept, after that we will introduce the research method and design employed, and then we discuss the reverse logistics archetypes developed based on literature review of reverse logistics.

2 Reverse Logistics Context

Terms like Reverse Channels or Reverse Flow appeared in the scientific literature in the 1970s, but consistently related to recycling [4]. The reverse logistic throughout the 1980s was about the movement of material against the primary flow [3]. The Council of Logistics Management (CLM) published the first known definition of Reverse Logistics in the early nineties as in [4] "…the term often used to refer to the role of logistics in recycling, waste disposal, and management of hazardous materials; a broader perspective includes all relating to logistics activities carried out in source reduction, recycling, substitution, reuse of materials and disposal." In the late 1990s Rogers and Tibben-Lembke defined reverse logistics as "The process of planning, implementing, and controlling the efficient, cost- effective flow of raw materials, in-process inventory, finished goods, and related information from the point of consumption to the point of origin for the purpose of recapturing or creating value or proper disposal" [12]. About the same time Dowlatshahi [5] defined reverse logistics as a process by which a manufacturing entity systematically takes back previously shipped products or parts from the point- of-consumption for possible recycling, remanufacturing, or disposal. A reverse logistics system in Dowlatshahi's definition constitutes a supply chain that is redesigned to systematically manage the flow of parts and products intended for remanufacturing, recycling, or disposal activities. With this definition, systems will be capable of effectively using resources that were not previously considered or utilised.

Generally the scope of reverse logistics has increased with the development of the topic as we see in Fig. 1. We can spot that also using the last two definitions stated, since the later one considered reverse logistics as an abstract process where the former one has extended the terms to be close to the original definition of supply chain management. The reverse logistic is closely related to product recovery management practices and strategy which have been used 20 years ago [11, 13]. The American Production and Inventory Control Society (APICS) dictionary

Fig. 1 Reverse logistics definitions evolution

defines reverse logistics as "a complete supply chain dedicated to the reverse flow of products and materials for the purpose of returns, repair, remanufacture, and/or recycling" [2].

Alshammari and Ball [1] presented a framework that captures five stages of reverse logistics parameters which are; user, collection channel, processes, new life, and commercial. The user stage covers the motivation of reverse logistics, retrieval points, and what is recovered presented and retrieval level. The collection channel stage covers where and how related parameters to collection. The reverse logistics related processes cover the enablers to the reverse logistics system and disposition choices for recovery. The new life stage presents where the recovered product can be deployed. Then the commercial stage presents prising parameters, cost, and potential benefits to such a process. In each stage they presented the key parameters that significantly impact the shape of reverse logistics. The key parameters are intended to capture the shape of any reverse logistics operation; however, not all will be present in a given operation thereby giving rise to distinction between types. That work was the potential starting point in developing reverse logistics archetypes that could be the basis for defining the set of significant factors that shape the reverse logistics success for firms. Across industrial sectors it is expected that operations can be clustered into a number of archetypes that typify different reverse logistics operations.

3 Research Methodology and Design for RL Archetype Development

To undertake the empirical research a literature review was undertaken to identify key parameters and dimensions that affect the reverse logistics process design. The research identified five stages for the parameters of the process as Alshammari and Ball [1] published earlier. Those stages formed the basis of discussion with participant to articulate semi-structure interviews about reverse logistics design with senior industrial experts with reverse logistics operations. Four companies were approached for the interviews that represent range of manufacturers including automobile industry, electrical, and electronics along with third-party logistics provider with expertise in reverse logistics operation. The results from those interviews were collected and coded to map the design of reverse logistics at each case. Then the results were clustered to generically represent the reverse logistics design archetypes. A total of 4 individual interviews lasting for 1 h were conducted, and 2 conference calls for participants were conducted to share thoughts about the proposed archetypes. After that a workshop were carried out for 2 h in collaboration with Ellen MacArthur Foundation for circular economy where the archetypes were presented to audience ranging from industrial experts and academics to further validate the archetypes. The feedback from the 20 participants in workshop session was positive and embedded in the model.

As described above, since the nature of the phenomena is based on description and explanation of conceptual modeling, a qualitative research with multiple case studies were deployed [9]. This is also as Yin [16] suggested because the phenomena cannot be explained in isolation of its social complexity; and it is needed to consider multiple subjective perspectives.

4 Reverse Logistics Archetypes

The study of reverse logistics archetypes is crucial since it provides the basis to design the reverse logistics activity. Developing reverse logistics archetypes could be the foundation for defining the set of significant factors that shape the reverse logistics success for firms. Across industrial sectors it is expected that operations can be clustered into a number of archetypes that typify different reverse logistics operations. This paper will present three, which are low value extended producer responsibility, service parts logistics, and advanced industrial products recovery.

By reverse Logistics archetypes we mean; prototypical model of how reverse logistics can be done in a very high level. Gobbi [7] have developed a mathematical model based on the value recovery of product benchmarking with Fisher's structure for the supply chain of innovative and functional products [6]. Gobbi's work concluded the same approach that Fishers proposed and we are using their classification to develop the reverse logistics archetypes. The main conclusion from Gobbi's design is that if the return is legislation driven then the reverse logistics need efficient design, whereas if the return is value driven it needed to be responsive which is analogous to Fisher's model.

Another researcher proposed different types of reverse logistic types related to the retail sector and the managing of legislated material. Triantafyllou and Cherrett [14] proposed four types of reverse collection, namely: Integrated outbound and returns network, non-integrated outbound and returns network, third party return management, and return to supplier collection system. In this approach the researcher assigned number of characteristics for each type. However, in our attempt to define the reverse logistics approach we defined generically the overall structure of the process without limiting the structure to the collection stage.

Fisher and Gobbi introduced features of responsive and efficient supply chain and reverse supply chain models. However, the data collection process of systems that exists based on responsive and efficient models do not distinguish the practices and structure. After analyzing data, this research revealed three typical structures of reverse logistics, hence archetypes for each were created. Two of the archetypes align closely to Fisher's and Gobbi's models and design but third one is revealed to capture the structure of complex model which needs to compromise effectiveness and efficiency. The defined archetypes captures the structure of the reverse logistics in the four main stages which are; user, collection, processing, and new life (re-marketing) as proposed by Alshammari and Ball [1].

4.1 Archetype 1: Advanced Industry Goods Recovery

This archetypes or reverse logistics is similar to Fisher's [6] responsive supply chain model. This archetype is designed around service quality, and seeking early disposition decision. The other key factors that shape this archetype are; high value of the products which result in high touch requirement in terms of de-installation, packaging and item security, low volume, and the need for direct trusted dedicated collection. This archetype commonly decentralized with direct or trusted collection. The visibility if required for this product type through monitoring or leasing model to increase it, or coordinate the take back program to increase volume. The primary focuse of this archetype is to maximize product return value. It also compromise between maximizing utalization of recovery infrastructure and requirement for minimizing leat time as Gobbi [7] mentioned in his design for reverse supply chain. Common examples of this archetype are Network, IT, Telecom equipment, Medical Equipment. Figure 2 has representation of the archetype.

4.2 Archetype 2: Products with Low Residual Value and EPR

The second archetypes is also similar Fisher's [6] efficient supply chain model where the key objectives are minimizing cost and maximising volume to get the

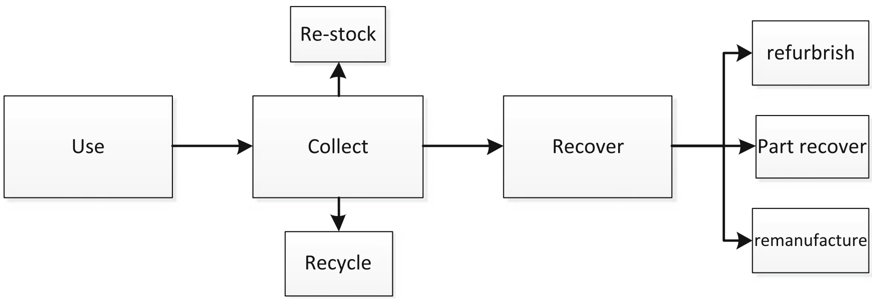

Fig. 2 Archetype 1 advanced industry goods recovery

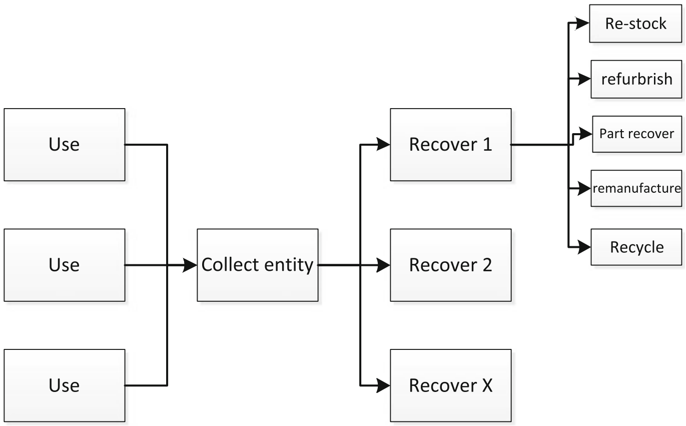

Fig. 3 Archetype 2 products with low residual value and EPR

economics of scale. The drivers for this approach are to recover raw material and fulfil extended producer responsibility (EPR) obligation. The return volumes are usually high, and have low residual value. Also there is not much of a concern for packaging, handling, and security. So for an effective structure it is better to standardise as much as possible. Develop centralised collection channel that capture items from multiple customer and consolidate for different recovery partner. The collection may come through municipal waste, point of sale, or drop-off. One key enabler for this model, especially for sectors that needs to comply with EPR, is to collaborate with partners who have similar interest. The primary areas of focus of this archetype are maximize recovery target as well as recycle efficiently the incoming volumes. Also maximize utilisation of recovery infrastructure, and reducing lead time as long as it does not increase the cost significantly as Gobbi [7] mentioned in his design for reverse supply chain. Common examples of this archetype are tires, consumer electronics, and shipping pallets. Figure 3 has representation of the archetype.

4.3 Archetype 3: Service Parts Logistics

This archetype could be seen as sub archetype where you can find dedicated transport and service partner who services multiple OEM as in archetype 2. The key different is that this model is between the previous two archetypes where collection could come from multiple customers through multiple or dedicated service provider. This archetype represents recovery of parts with significant residual value mainly at volume. It is established to ensure supply of replacement parts and services and as a formal process for remanufacturing. There is a potential for consolidation and pre-sorting before the recovery point. Key enablers for this

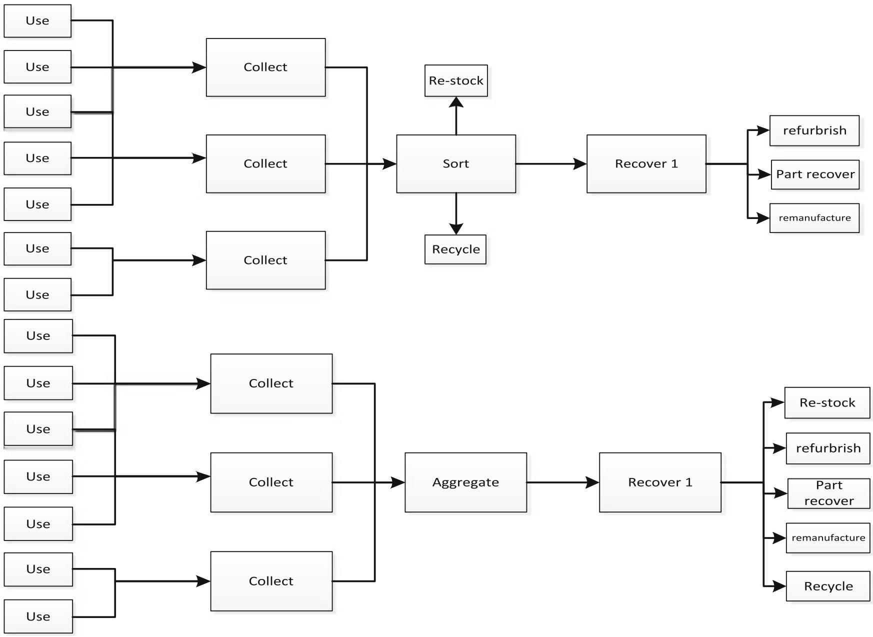

Fig. 4 Archetype 3 service parts logistics

structure are effective traceability of items and buy/take back scheme to make the economics of the system, and long term partnership in regulated markets [15]. The primary focus of this archetype varies based of the business model, product complexity, and level of competitiveness in that market. Common examples of this archetype are Machinery and heavy equipment parts, automotive parts, other spare parts, recyclable waste. Figure 4 has representation of the archetype.

5 Conclusion

The reverse logistics analysis tools are not available or not well structured [11]. Majority of the work is on exploration of the subject, however in order to establish the tools we need to accurately address the processes through modelling and standardising the activities. From these base models, we can develop the analysis tools that fulfil the need of this area. The challenge for industry is the absence of models to support the development of reverse logistics operations. This absence is both in practice and in the literature.

In this paper we developed reverse logistics archetypes as a basis for defining the significant factors that shape the reverse logistics success for firms. Across industrial sectors operations can be clustered into a number of archetypes that typify different reverse logistics operations, for example products with low residual value and advanced industrial goods recovery could be operated in the same company.

The purpose of the archetypes is to capture the dominant factors that shape the reverse logistics design and support communication of the topic through referring to proposed archetypes and amend the structure as necessary.

Ultimately, by collecting data on reverse logistics operations against those archetypes it is expected that different levels of maturity will be uncovered. In turn, companies could use this to understand where they stand in relation to what has been achieved in other businesses and use this as a tool to question where they should change practice in order to improve performance.

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Part III
General Track 3: Sustainable Manufacturing Systems and Enterprises

Sustainable Manufacturing Systems Based on Demand Forecasting—Supply Chain Sustainable Growth

Martin Hart, Pavel Taraba and Jiří Konečný

Abstract Contemporary business environment is characterized by a high level of dynamics development and by competitive advantage. There is an increasing demand on both living environment protection and effective management of supply chains of particular industries. Supply chains have been becoming more complex and bulkier in the light of streaming material flows. One of the bases of a long-term socio-economic development of society in current global business environment is effective planning, management and control of bulky material flows of supply chains. Company's management systems and also manufacturing management systems should be based on a forecasting subsystem of an independent demand or consumption. An accurate demand forecast enables adequate production of final products, parts, etc., although there is no overproduction or shortage. In final consequence the manufacturing systems based on progressive forecasting subsystems represent one of the main parts of supply chains in context of living environment protection and long-term sustainable development—thus the production or material flows are adequate within particular regional or global supply chains. This article deals with current issues of effective manufacturing systems of supply chains based on prognostic subsystems of independent demand or consumption.

Keywords Manufacturing systems · Supply chain management · Sustainability · Demand forecasting · Methodology

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1 Introduction

Design of effective manufacturing systems represents basis for long-term sustainable supply chains of particular industrial branches. It mainly concerns the achievement of a required level of flexibility on the one hand and a required level of stability on the other hand. Design of effective manufacturing systems is one of the presumptions of long-term sustainable supply chains of particular industrial branches. It primarily concerns achievement of a required stability level. At present time the manufacturing systems based on forecasting subsystems of independent demand or consumption should be the cornerstones of regional or global supply chains where there should not be overproduction or shortage and there will be an assured continuous material flow.

The effective management of bulky material flows of a supply chain should have a positive impact on the socio-economic development of the society and on the living environment protection [1].

Then due attention should be paid to planning, management and control issues of the supply chains or if you like the flows streaming in them. The accurate forecasts of demand or consumption patterns present a basis to create company's plans, and that is particularly applied from the perspective of given functional levels. Currently the supply chains are considerably complex; the forecasting and planning processes of companies should be innovated with the aim to enhance the efficiency and the effectiveness of bulky material flow management. Together with the supply chain complexity there are increasing requirements for its management and there is also an increasing vulnerability in the sense of the origin of a crisis situation.

The trend of the growing material flow volume of the world's economy and therefore also the need of effective company's management systems is illustrated in Fig. 1. According to Fig. 1 an increasing linear trend of 4 chosen world's economy indicators in the first 14 years of 21st century is evident.

Therefore, this paper will briefly explain main notions such as supply chain, forecasting, manufacturing and system approach at the beginning and then it will state a general case study describing how the manufacturing system can be innovated aiming at a company's prognostic subsystem.

2 Supply Chain Definition

A supply chain can be defined as a network consisting of bundles which are represented by companies, central distribution warehouses, wholesales, retails and customers. The integral part of a supply chain is transport or the flows which stream within a supply network—material, financial and information. The supply chain is unique for each industrial branch or each company. One can speak about internal and external supply chains. A general supply chain and its particular parts are illustrated in Fig. 2.

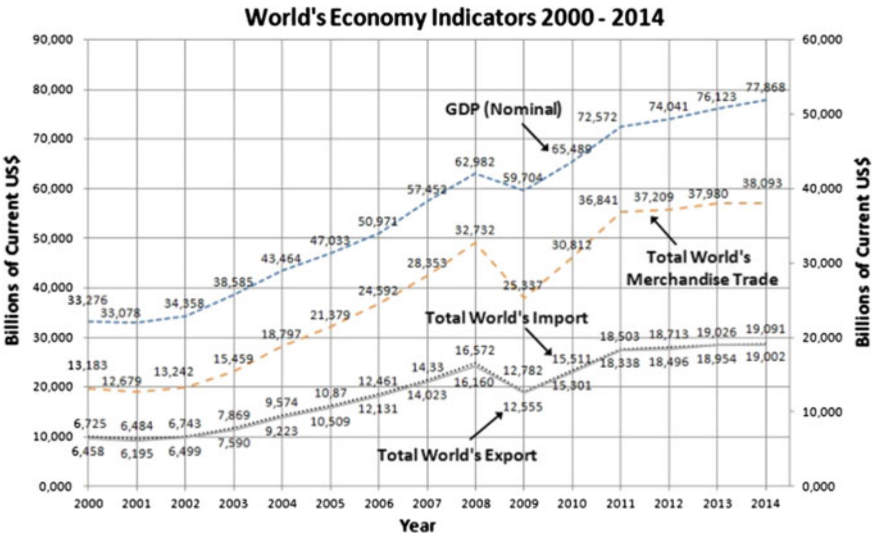

Fig. 1 World's economy indicators 2000–2014 [2]

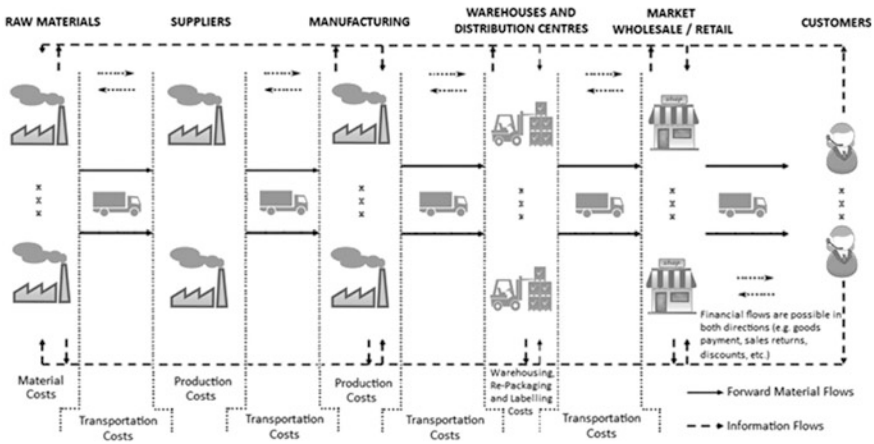

Fig. 2 Illustration of a general supply chain [3]

Deeper development of a supply chain structure started in 1950s and it was closely connected to growing trends of global market globalization. 21st century can experience development of new markets, for instance the common EU market, new markets of developing countries (China, India); supply chains are characteristic for their complexity, volume and number of the flows streaming in them [3]. The processes of planning, management and control are difficult in such dynamically developing supply chains; and thus new methods or methodology should be developed in order to simplify management of a complex supply chain. Contemporary supply chains should be balanced from the view of two opposite criteria—flexibility and stability.

In some nodes the inventory can be accumulated, in others the shortage can occur and then it can result in a customer loss. Another very important feature of present supply chains is their vulnerability regarding various types of crisis situations—for example a decrease in demand, natural disaster, security threat, etc. [4].

Management systems of supply chains or company's management systems should be able to respond lively to changing markets requirements, particularly to a changing demand and to a potential crisis situation. These systems should also represent foundations to ensure material flow stability, thus the effectiveness and the efficiency of a supply chain. Therefore, effective supply chain management systems or company's management systems should have a positive impact on the quality of society and on socio-economic development and that can be applied to both regional and global extent [1].

Even the level of living environment protection is related to the quality of the above stated management systems [1].

3 Demand Forecasting

Both the character and level of a demand play a significant role at managerial decision making at all functional levels of a company or at all parts of supply chain. The accurate demand forecasts or a consumption are necessary for creation of effective master plans which can be applied to all managerial processes related to internal material flow and external material flow, and then for the supply chain management. Prognostic methods can be classified into two main groups, namely the quantitative methods and qualitative methods of forecasts creation. It is possible to combine both of the method groups with the aim to reach more accurate prognosis of demand or consumption development.

The more variable a demand is, the higher weight should be given to qualitative forecasting methods [3, 5].

Selection of a suitable forecasting method is particularly determined by a demand pattern. Various demand patterns are illustrated in Fig. 3.

A leap demand is featured by leap changes in a demand level at particular time periods; rather a stable phase of a demand pattern can succeed after a change in a demand level.

The following example can be stated: a demand for a production machine spare part; with an increasing rotation speed, there is a growing need for changing a machine spare part and vice versa. Other examples of a leap demand can express obsolescence or crisis situation occurrence. For example rapid electronic component obsolescence can cause a leap change of some product demand in the market. When a crisis situation occurs, a demand increases for instance medical supplies.

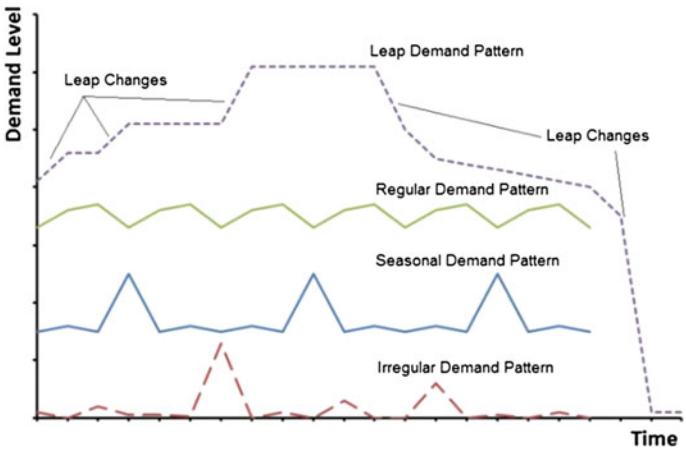

Fig. 3 Essential demand pattern [3, 5]

Regular demand is characterized by more or less stable course of time. A demand for basic pastry can be stated as an example. Seasonal demand is characterized by a positive increase or negative decrease in the given time period. The ice cream demand during summer time can be stated as an example. Irregular demand is typical for casual changes in level at occasional time intervals. Spare parts consumption can be mentioned as an appropriate example. With current dynamic development of market and social-cultural environment, the knowledge of a demand pattern and its level is becoming more and more important; that fact can be applied to the context of both regional supply chains and global supply chains—management systems. Further on, we can distinguish between a dependent demand and an independent demand where the knowledge of the independent demand is crucial for deriving the dependent demand. Next, with respect to time, it is possible to talk about a continuous and non-continuous demand [6, 7].

4 Manufacturing

Manufacturing is the main element of economy; it is the transformation of inputs into outputs. Manufacturing systems integrate all processes in terms of the layout of production spaces, with the aim to ensure fluent material flow. The projection of manufacturing systems represents primarily the design of:

- deployment of production units and equipment,
- material flows,
- production capacities,
- lead time production,
- inventory level of semi-finished products,

- maintenance plans and
- investments.

It is possible to classify manufacturing into the following groups according to production volume:

- project manufacturing—a set of production activities to get a unique product,
- single-part production—a production of a specific type of various products in small quantity,
- series production—a production of one or several similar products/services,
- mass production—a production of uniform products/services.

The basis of efficiency and effectiveness of manufacturing systems is represented by forecasting subsystems which supply necessary input data for high-quality production plans creation and related activities. Manufacturing as one of the functional parts of a company should be based on system and process management principles while managerial decisions in production department should be based on forecasts of an independent demand or consumption. As a result, properly designed production systems lead to low production costs, high productivity, flexibility, optimally used production capacities, to high quality and production speed, properly managed waste management and minimization of the negative impact on living environment [8, 9].

5 System Approach and Manufacturing Systems

System approach, then the visualization, real system description and its transformation to general systems are vital for solving the issues related to contemporary supply chains or if you like manufacturing systems as the main element of supply chains. It mainly involves the issues of creating new methods and new methodologies.

Methodology includes a list of methods, their description and wide principles or rules from which specific methods or procedures may be derived to interpret or solve different problems within the scope of a particular discipline. Unlike an algorithm, the methodology is not a formula but a set of practices [3, 5, 10].

Methodical approach can be described as a set of points through which one can reach determined goals. In simple terms it is a sequence of steps to reach a desired aim.

A method can be defined as a scientific–systematic procedure towards reaching an aim or if you like gaining a required output with a required accuracy and efficiency. Achieved results should declare the desired level of validity and reliability.

Thus, the system approach can be understood as system thinking that emphasizes the interdependence and interactive nature of elements of both the internal and external analysed system or, more precisely, of an organization.

To tackle a problem nowadays usually requires usage of both systematic approach and modelling while the real systems need to be transformed to general systems with mathematical–statistical expression and visualization [3, 5, 10].

As for the issues concerning current supply chains—e.g. simplicity, processability, integrability, flexibility, stability, resilience, security, etc., the issue of production plants should also be systematically solved using the system approach and principles of process analysis.

A manufacturing system can be defined as an organized set of production–manipulation (machines) and labour capacities and then a set of material, information and financial flows.

Each manufacturing system includes a specific number of production–transformation processes, maintenance processes and a specific number of administration processes. The manufacturing system performs planning, management and control function as well and that mainly applies in terms of production planning and labour resources, material flow management and semi-finished products inventories.

The manufacturing system structure can be graphically expressed using a layout, see Fig. 4.

The increase in effectiveness and efficiency of industrial companies manufacturing systems as a part of a supply chain can lead in final consequence to:

- increase in supply chain material flows fluency,
- flexibility improvement and stability of supply chaos,
- supply chain effectiveness and efficiency improvement,
- enhancement of socio–economic development of society,
- cost optimization,

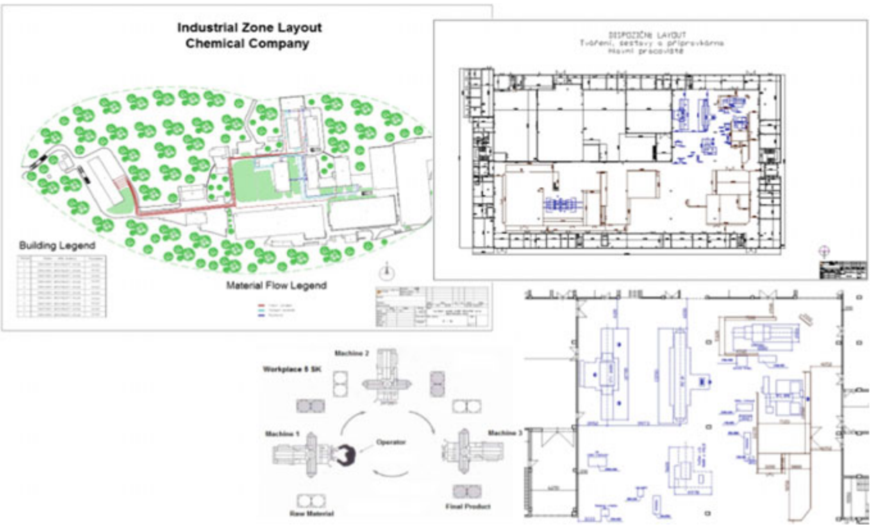

Fig. 4 Illustration of different detail level of layouts [10]

- increasing competitive advantage,
- reinforcement of a supply chain resilience against crisis situations,
- reduction of negative impacts of supply chains on the living environment [4, 11].

6 General Case Study

An industrial food company optimizes its production management system in accordance with current development of regional and global business markets, thus also in compliance with up-to-date development of supply chains. After performing an analysis of a current state of the production management system within the frame of solving a production management system optimization project, it has been decided that firstly it is necessary to innovate the company forecasting subsystem which will supply input data for high-quality managerial decisions in a particular production department of a respective industrial company. For these purposes, the methodology has been used to create an independent demand forecasting system which has been developed in the dissertation thesis by Hart, published in 2010.

The methodology for creating an independent demand forecasting system in an industrial company (199 pp.) can be briefly described mentioning the following 8 consecutive essential points:

1. **Company description** or more precise specification of production plants for which a forecasting system of demand or consumption is to be created,
2. **Visualization of supply chain**—inner and outer flows,
3. **Determination of order penetration point** or points within the scope of a company supply chain—identification of a demand with independent or dependent character,
4. **Segmentation of extensive inventory portfolio** (e.g. final product, semi-finished product, raw materials) accumulated in order to penetrate a point or points,
5. **Analysis of existing systems** for independent demand forecasting,
6. **Determination and statistical processing of input data** for a demand forecasting (demand, consumption, sales),
7. **Essential analysis of demand pattern**—trend, seasonality, increase, decrease,
8. **Finding a process of the best-fit models to forecast** independent demand for single inventory segments accumulated in order penetration point or points of a company supply chain [12].

Briefly described methodology has been subsequently applied in the food company with the aim to innovate; it means with the creation of a new forecasting subsystem.

Based on a newly created forecasting subsystem the forecast for a total monthly demand of final products has been made as the main prognostic outcome, see Fig. 5.

Fig. 5 Forecast for a total monthly demand level of final products produced in the company which has been generated using a mixed forecasting model —70 % ARIMA (2, 2, 2) and 30 % expert judgement /the second table shows forecast for a total monthly demand level of final products produced in the company which will not be exceeded by the real demand values in the year 2015 and that is for sure with 95 % probability [3]

The Forecast for the Year 2015

January 15	2 316
February 15	1 855
March 15	2 535
April 15	2 181
May 15	2 773
June 15	3 921
July 15	3 264
August 15	2 883
September 15	2 567
October 15	2 046
November 15	2 439
December 15	1 374
Sum [t]	30 154

ARIMA (2, 2, 2)
MAPE = 0,85%

The Forecast for the Year 2015 - The Upper Limit of the Accuracy of the Total Demand Level Forecast

January 15	2 357
February 15	1 914
March 15	2 607
April 15	2 264
May 15	2 865
June 15	4 022
July 15	3 373
August 15	3 000
September 15	2 692
October 15	2 177
November 15	2 576
December 15	1 518
Sum [t]	31 365

Function of the newly created prognostic subsystem is to generate accurate forecasts as the input data for high-quality managerial decisions at particular functional parts, which should be the main positive effect on entire company running.

After the innovation of the company prognostic subsystem, particular subsystems and processes of a company manufacturing system including the layouts of production operations and semi-finished products warehouses have been consequently innovated as well. Above all there have been planning, management and control of subsystems of the production–handling and labour capacities.

Further on, there have been the optimization of semi-finished products inventories and the optimization of material flows within the scope of the mentioned company manufacturing system.

Data of an innovated company prognostic subsystem is consequently used for the needs of effective planning, management and control of all production capacities, flows, inventories and processes, see Fig. 6.

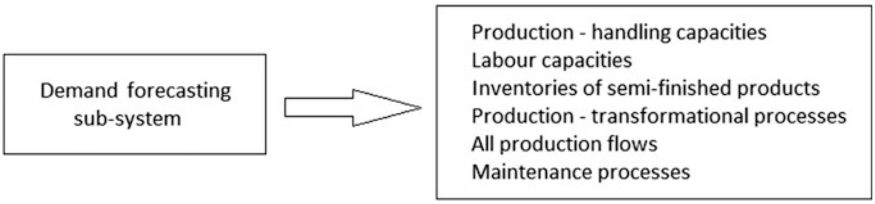

Fig. 6 Demand forecasts data as the input for manufacturing managerial decision making [3]

7 Conclusion

With respect to current global world market, the effective material flow management within the scope of the supply chains of particular industrial branches is becoming one of the essential prerequisites for long-term sustainable socio-economic development and living environment protection. To avoid an overproduction or a shortage both in regional and global supply chains—thus to achieve the right level of flexibility and stability of supply chains, it is necessary to apply prognostic subsystems of an independent demand to plan effectively.

This paper described contemporary character of supply chains. There was stated knowledge of demand forecasting and system approach, which is necessary to design the manufacturing systems.

Effectiveness and efficiency of the manufacturing systems represent main presumption to reach a long-term sustainable development both in regional and global scale. Manufacturing systems present a leading element of supply chains in which the additional value is increasing and thus the due attention should be paid to them. Effective management of manufacturing systems should be based on prognostic subsystem of an independent demand which would supply input data—the forecasts for high-quality managerial decisions as it is stated in the case study of this paper. It particularly concerns the issues of effective planning, management and control of production—handling capacities, labour resources, semi-finished products inventories, production transformation processes and maintenance processes. The important role through the projection of effective manufacturing systems is also played by the design issues of production and warehousing spaces and related production flows, see the article "Layout Drawing Documentation as the Basis of Logistics Management System of a Company".

At present, the manufacturing systems should be designed to meet the following fundamental presumptions:

- flexibility,
- stability,
- resilience against crisis situations,
- security.

If the manufacturing systems meet the 4 above stated prerequisites at a required level and they are based on subsystems of an independent demand forecasting, they should significantly enhance the stability of economy in regional or global scale.

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An Analysis of Indirect Water Withdrawal and Consumption in Automotive Manufacturing Facilities

Bert Bras and Andrew Carlile

Abstract Water is a key resource for all life. Recent droughts have also exemplified the importance for manufacturers to understand their impact on water resources. While most manufacturers typically know the amount of water they use in their facilities, they have little knowledge about the indirect effects they have on water resources. In this paper, the indirect impact from electricity use by automakers on water resources is examined. Water withdrawal and consumption from electricity use by hypothetical but representative facilities around the world is quantified and analyzed. The results indicate that the water withdrawal and consumption caused by the use of electricity is larger than the direct water use and consumption in the facilities themselves.

Keywords Water withdrawal · Consumption · Automotive · Electricity

1 Introduction

For automotive manufacturing in general, the water use is an important resource because it impacts cost, brand image, and the relationship with the local actors near facilities [1]. Many automakers are tracking direct facility use of water. This direct water use or withdrawal is, however, only a partial accounting of the impact auto manufacturing has on water resources. Analogous to scope 1, 2, and 3 greenhouse gas emissions, manufacturers also have indirect water use, withdrawal and consumption. Having a complete understanding of the indirect water use is important, because even if the water is not directly withdrawn for a facility, that water is removed from the source and is unavailable for other purposes, which can increase the stress in a location [2]. This paper examines significant indirect water impact that can occur from electricity generation.

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2 Hypothetical Automotive Company (HAC) with Global Production

2.1 Automotive Manufacturing Facility Location and Water Data

For the analysis, a Hypothetical Automotive Company (HAC) was created based on public data collected about current automotive manufacturers. For example, Volkswagen lists their facilities and many production and worker figures publically [3, 4]. Ford [5], Subaru [6, 7], Hyundai [8], BMW [9], and Fiat-Chrysler [10] have similar public references. All of the HAC locations are located close to, or exactly at, a location from one of these automakers. For example, the USA Car and Truck locations are located near Detroit where Ford, GM, and FCA all have substantial factories. The India Car and Truck are located near Chennai, India, which is a very industrial area with automotive production. The Germany Car location is located near numerous vehicle factories. Mexico Car, China Car and Truck, Japan Car and Truck, South Korea Car, and Brazil Car and Truck are all located close to other automotive manufacturing locations as well. A notable location is the UK Super Luxury Car location, which is loosely modeled from Bentley [4].

Water data was collected form Corporate Sustainability Reports and web searches for various automakers in order to create hypothetical but representative automotive production facilities in varies parts of the world. Both car and truck production facilities are included, as well as a "luxury car" production facility. These facilities and their representative of water data is presented in Table 1. The

Table 1 Water data for representative global facilities for hypothetical automotive company (all water values are in m^3/year)

Facility name	Surface water	Ground water	Municipal water	Total withdrawal	Discharge	Recycled	Total consumption
USA car			400,000	400,000	200,000	100,000	100,000
USA truck			800,000	800,000	400,000	200,000	200,000
India car	200,000			200,000	100,000	50,000	50,000
India truck	400,000			400,000	200,000	100,000	100,000
Germany car			500,000	500,000	250,000	125,000	125,000
Mexico car	200,000			200,000	100,000	50,000	50,000
China car		200,000		200,000	100,000	50,000	50,000
China truck			400,000	400,000	200,000	100,000	100,000
Japan car			400,000	400,000	200,000	100,000	100,000
Japan truck			800,000	800,000	400,000	200,000	200,000
South Korea car			2,000,000	2,000,000	1,000,000	500,000	500,000
Brazil car	200,000			200,000	100,000	50,000	50,000
Brazil truck	400,000			400,000	200,000	100,000	100,000
UK super luxury			110,000	110,000	55,000	27,500	27,500

Table 2 Water data for representative global facilities per unit production (all water values are in m^3)

Facility name	Country	Production (vehicles)	Withdrawal per vehicle	Consumption per vehicle
USA car	USA	100,000	4.00	1.00
USA truck	USA	200,000	4.00	1.00
India car	India	50,000	4.00	1.00
India truck	India	100,000	4.00	1.00
Germany car	Germany	200,000	2.50	0.63
Mexico car	Mexico	50,000	4.00	1.00
China car	China	50,000	4.00	1.00
China truck	China	100,000	4.00	1.00
Japan car	Japan	100,000	4.00	1.00
Japan truck	Japan	200,000	4.00	1.00
South Korea car	South Korea	500,000	4.00	1.00
Brazil car	Brazil	50,000	4.00	1.00
Brazil truck	Brazil	100,000	4.00	1.00
UK super luxury	United Kingdom	2000	55.00	13.75

country of location of each facility is given in Table 2 as well as each facilities production. The Super Luxury car plant has the highest per vehicle impact, which is not surprising due to the low production volume and resources spent in producing these super luxury cars.

2.2 *Electricity Consumption for Vehicle Production*

The manufacturing of vehicles requires the use of electricity, and that electricity usage also contributes to indirect water use [11]. Automotive manufacturing companies track their energy use and disclose it in their corporate sustainability reports (CSR). Table 3 is a collection of these values from six different major automakers. Not all automakers report electricity use in their corporate sustainability reports, but averages of 2.15 MWh of total energy needed to produce a vehicle of which 1 MWh is electricity seem to be good assumptions. Not all energy needed to produce a vehicle is in the form of electricity. A large portion of the rest of the total energy is mostly natural gas, which is typically used to heat facilities and also for powering so called powerhouses that generate steam, compressed air and sometimes even some on-site electricity for the facilities. For the analysis in this paper, the average value of 0.99 MWh/vehicle will be used in conjunction with the automotive facility profiles for the indirect usage calculation of total electricity. The average electricity needed to produce a vehicle can be used with the facility production amounts to examine the electricity use for the facilities.

Table 3 Energy intensities from various automakers CSR's in MWh/Vehicle

Automaker	Total energy consumption per vehicle (MWh/vehicle)	Electricity consumption per vehicle (MWh/vehicle)
GM [12]	2.19	
Volkswagen [13, 14]	2.21	1.08
Ford [15]	2.44	
Nissan/Renault [16]	2.19	1.00
Peugeot SA [17]	1.46	0.80
BMW [18]	2.40	1.06
Average	2.15	0.99

3 Water Impact of Electricity Generation

3.1 Water Impact of Different Generation Technologies

Many different researchers and organizations have calculated values of water withdrawal and consumption by energy generation type for the use in life cycle assessments. Two papers that aggregate some of these results are by Semmens et al. [11] and Dooley et al. [14]. Table 4 is a collection of the information used to calculate the indirect water withdrawal and consumption. These are some averages for current technologies. Some of these numbers can change significantly if, e.g., different state-of-the-art cooling technologies are used in the future. Notable are the low consumption and withdrawal amounts for photovoltaics (PV). The only water really needed is for cleaning PV panels, making this renewable energy source not only excellent option for reducing greenhouse gas emissions, but also for reducing water consumption and withdrawal. The other extreme is hydroelectric power generation which has large consumption amounts due to water evaporation from its lakes. Withdrawal is zero because water is not altered when it passes through hydroelectric turbines.

Table 4 Water consumption and withdrawal values for electricity sources in m^3/MWh

Electricity source	Water consumption [11]	Water withdrawal [14]
Coal	0.871	80.90
Natural gas	0.547	25.23
Nuclear	1.643	98.59
Hydroelectric	17.000	0
Solar (PV)	0.023	0.02

Table 5 Electricity resource profile for selected countries [19]

	Coal (%)	Natural gas (%)	Nuclear (%)	Solar (PV) (%)	Wind (%)	Hydro (%)
Brazil	2.6	8.5	2.9	0.0	0.9	75.2
China	75.8	1.7	2.0	0.1	1.9	17.5
Germany	45.6	12.3	15.8	4.2	8.0	4.4
India	71.1	8.3	2.9	0.2	2.5	11.2
Japan	29.3	38.4	1.5	0.7	0.5	8.1
Mexico	11.7	51.4	3.0	0.0	1.2	10.8
South Korea	44.8	20.9	28.1	0.2	0.2	1.4
UK	39.6	27.5	19.4	0.3	5.4	2.3
USA	38.3	29.5	18.7	0.2	3.3	7.0

3.2 Electricity Generation Grid Mix by Source for Different Countries

With the water use information for different sources, the other piece of information needed to calculate the indirect water use by electricity is to find the electricity resource profiles for the countries where the HAC operates. The IEA [19] tracks the electricity resource profiles of a majority of countries worldwide. The IEA statistics were in GWh for each type of resource, so to create a percentage profile, the GWh for each resource was divided by the total GWh for that country, and included in Table 5.

With the average electricity use for a vehicle, water withdrawal and consumption for different types of electricity generation, and the resource profiles of the countries in which the HAC operates, it is now possible to calculate the indirect water withdrawal and consumption for the HAC.

3.3 Calculation of Indirect Water Withdrawal and Consumption by Energy

The HAC profile established a realistic production number for the different facilities with respect to their location. With realistic production information and the average energy intensity use from automakers CSR's it is possible to calculate the electricity usage for each facility. With the country based electricity resource profile, the MWh usage by each facility can be broken down by electricity source, which can be multiplied by the water withdrawal or consumption information to find the indirect withdrawal or consumption for each facility by means of Eqs. (1) and (2).

$$
\begin{aligned}
\mathit{Indirect\ Withdrawal}\left[\frac{\mathrm{m}^3}{\mathrm{year}}\right] = {} & \mathit{Annual\ Production}\left[\frac{\mathit{vehicle}}{\mathrm{year}}\right] \\
& * \mathit{Elec.\ Intensity}\left[\frac{\mathrm{MWh}}{\mathit{vehicle}}\right] \\
& * \sum \mathit{Resource\ Profile}\ [\%] \\
& * \mathit{Water\ Withdrawal\ by\ Resource}\left[\frac{\mathrm{m}^3}{\mathrm{MWh}}\right]
\end{aligned} \tag{1}
$$

$$
\begin{aligned}
\mathit{Indirect\ Consumption}\left[\frac{\mathrm{m}^3}{\mathrm{year}}\right] = {} & \mathit{Annual\ Production}\left[\frac{\mathit{vehicle}}{\mathrm{year}}\right] \\
& * \mathit{Elec.\ Intensity}\left[\frac{\mathrm{MWh}}{\mathit{vehicle}}\right] \\
& * \sum \mathit{Resource\ Profile}\ [\%] \\
& * \mathit{Water\ Consumption\ by\ Resource}\left[\frac{\mathrm{m}^3}{\mathrm{MWh}}\right]
\end{aligned} \tag{2}
$$

These equations follow the standard practice used to calculate the water consumption and withdrawal from electricity sources [11, 14]. The novelty of calculating both types of water use is that withdrawal is typically not calculated as an indirect use. Many CSR's from automakers include indirect CO_2 emissions, indirect waste, or indirect water consumption, but none documented include indirect water withdrawal due to energy [12, 13, 15–18, 20].

4 Indirect Water Withdrawal and Consumption

4.1 Results

The indirect withdrawal and consumption from electricity are shown in Table 6. The results also include total electricity per facility. The withdrawal and consumptions are also normalized by vehicle production in cubic meters per vehicle.

4.2 Discussion

As can be seen, the indirect withdrawal from electricity for the HAC facilities is substantially higher than the direct withdrawal by the facility. The per vehicle direct withdrawal numbers are typically from 2 to 6 m^3 (with UK Super Luxury being 55 m^3 which is not surprising due to the low production volume and high resource use for very expensive super luxury cars like Bentleys.

Table 6 HAC facilities indirect water withdrawal and consumption due to electricity

Facility	Total electricity per facility (MWh/year)	Total indirect withdrawal per facility (m^3/year)	Total indirect withdrawal per vehicle (m^3/vehicle)	Total indirect consumption per facility (m^3/year)	Total indirect consumption per vehicle (m^3/vehicle)
USA car	98,500	5,597,981	55.98	198,915	1.99
USA truck	197,000	11,195,962	55.98	397,830	1.99
India car	49,250	3,076,605	61.53	130,078	2.60
India truck	98,500	6,153,210	61.53	260,156	2.60
Germany car	197,000	10,942,563	54.71	430,950	2.15
Mexico car	49,250	1,248,333	24.97	112,220	2.24
China car	49,250	3,135,674	62.71	181,830	3.64
China truck	98,500	6,271,349	62.71	363,655	3.64
Japan car	98,500	3,440,265	34.40	195,037	1.95
Japan truck	197,000	6,880,531	34.40	390,067	1.95
South Korea car	492,500	34,092,550	68.19	613,102	1.23
Brazil car	49,250	348,295	6.97	635,178	12.70
Brazil truck	98,500	696,590	6.97	1,270,347	12.70
UK luxury car	1970	114,414	57.21	2485	1.24

Indirect consumption due to electricity use is substantially lower than withdrawal. This is due to most types of electricity generation having low evaporative losses. Intuitively, the indirect consumption will be orders of magnitude lower for all of the electricity sources except hydroelectric, which has an average water consumption of 17 m^3/MWh due to the high evaporation rates for standing water in lakes [11, 14].

The indirect water consumption values calculated for the HAC facilities not located in Brazil are all within the range of 1.23–3.64 m^3/vehicle. Facilities in Brazil have substantially higher consumption due to the increased use of hydroelectric power in that country. The consumption by Brazilian facilities is in the range of high 12 s m^3/vehicle. The average consumption for the HAC facilities overall is 4.22 m^3/production, but without the Brazilian facilities it is calculated as 2.26 m^3/production. These values broadly agree with the results by [11] shown in Table 7. The average of the automakers from Semmens' calculation was 2.21 m^3/vehicle which is below the average of the HAC facilities (not located in Brazil), which tended to be close to the Daimler value of 3.69 m^3/year [11]. Given that the HAC profile is hypothetical and different sources from Semmens were used, the consumption values are reasonable.

Table 7 Results for indirect water consumption by electricity from [11]

Automaker	(m^3/vehicle)
BMW	1.91
Chrysler	3.32
Daimler	3.69
Ford	2.41
GM	1.80
Honda	2.27
Hyundai	2.25
Kia	1.24
Mazda	2.12
Nissan	1.54
Volkswagen	1.77
Average	2.21

5 Comparison with Direct Withdrawal and Consumption

In order to compare the ratio of indirect water withdrawal from electricity to the direct withdrawal from the facilities themselves, a factor called Indirect Electricity Withdrawal Factor (IEWF) is created to show this ratio. The IEWF is simply the Total Indirect Withdrawal per Vehicle divided by the Direct Withdrawal per Vehicle.

This factor is a measure of how much more water is being withdrawn by the indirect use than the direct use. For Example, the Germany Car facility is the most water efficient of all the car assembly facilities, but it has an IEWF of 21.9. This is due to Germany having an electricity resource profile that is heavy on coal and nuclear (80.9 and 98.59 m^3/MWh, respectively). The Brazilian facilities have very low IEWF's (1.74) because Brazil uses a substantial amount of hydroelectric which has a negligible water withdrawal. However, in the consumption calculations the reverse is true.

The IEWF may be a useful concept because it enables automakers (or other manufactures') to prioritize which impacts from their facilities are causing constraints on the supply to a location. Although water withdrawn for electricity generation typically has a very high return ratio (the vast majority of the water returns to the source for other users [14]) it can still cause availability problems [21].

For the indirect consumption of water due to electricity generation, no factor relating to the direct withdrawal will be made for two reasons: First, the overwhelming reporting of water use by automakers is direct withdrawal. Second, it does not appear to vary much between facilities based on the calculation (Table 8).

Table 8 HAC facilities indirect electricity withdrawal factor results

Facility	Indirect withdrawal per vehicle (m^3/vehicle)	Direct withdrawal per vehicle (m^3/vehicle)	Indirect electricity withdrawal factor (IEWF)
USA car	55.98	4.00	13.99
USA truck	55.98	4.00	13.99
India car	61.53	4.00	15.38
India truck	61.53	4.00	15.38
Germany car	54.71	2.50	21.89
Mexico car	24.97	4.00	6.24
China car	62.71	4.00	15.68
China truck	62.71	4.00	15.68
Japan car	34.40	4.00	8.60
Japan truck	34.40	4.00	8.60
South Korea car	68.19	4.00	17.05
Brazil car	6.97	4.00	1.74
Brazil truck	6.97	4.00	1.74
UK luxury car	57.21	55.00	1.04

6 Discussion

The indirect water either withdrawn or consumed by the electricity generation for automobile production is an impact that is not currently covered in CDP Water Disclosures [1] of CSR's electricity [12, 13, 15–18, 20]. Despite this, the indirect use in electricity generation can be orders of magnitude larger than the direct withdrawal by automotive manufacturing facilities.

The use of indirect withdrawal and consumption for electricity generation is also not typically included when calculating life-cycle-assessments of the impact of vehicles. Only very few studies include indirect water consumption for a life-cycle-assessments [11].

Including the indirect withdrawal due to electricity generation can potentially be used to show the benefits of switching from non-renewable sources to renewable sources, excluding hydroelectric due to the dramatic consumption (17 m^3/MWH). Solar and wind power can dramatically reduce the indirect water withdrawal and consumption, but the effect is more pronounced in the indirect withdrawal. In Table 9 the HAC USA Car facility is compared with a facility called Solar Country Car. The only difference between the two facilities is the USA Car facility uses the USA electricity source profile from IEA [19] and the Solar Country Car facility uses entirely photovoltaic (PV) solar power.

The difference in indirect water withdrawal and consumption is dramatic, particularly the withdrawal, which is over 2000× times greater for the USA Car facility. Even the indirect consumption by USA Car is over 80× the indirect consumption by the facility that uses exclusive solar PV power. The electricity usage to manufacture

Table 9 USA car compared with solar powered car facility

Facility	Total indirect withdrawal for electricity (m^3/year)	Total indirect consumption for electricity (m^3/year)	Total indirect withdrawal per vehicle (m^3/vehicle)	Total indirect consumption per vehicle (m^3/vehicle)
USA car	5,597,981	198,915	55.98	1.99
Solar country car	1980	1980	0.02	0.02
Difference	5,596,001	196,935	55.96	1.97

cars and the energy profile of the countries in which the facilities are located is an underrated aspect of the water impacts of automotive manufacturing. Due to their low water withdrawal and consumption, car companies should pursue implementation of photovoltaics renewable energy on-site. For example, Bentley Motors constructed a 5 MW rooftop photovoltaic system at its site in Crewe, U.K. which covers about 40 % of the factory's power demand [13, 14]. Although the primary focus for this installation seems to have been related to greenhouse gas emissions savings, this PV array would also reduce the factory's indirect water withdrawal and consumption dramatically due to the low impact of electricity from PV.

7 Conclusion

Although many manufacturers are familiar with their direct water use, few have any idea about their indirect impact on water resources. As shown, the amounts of water withdrawn and consumed as a result of electricity generation for automotive production facilities surpass the amount of water directly used and consumed in facilities. Thus, manufacturers should not only focus on reducing direct water use in their facilities, but also electricity use. This has a synergistic benefit from an environmental and financial perspective. It also highlights the need of researches to focus on the water-energy nexus that is becoming more and more important. For example, on-site installations of photovoltaic panels for electricity generation not only reduce greenhouse gas emissions, but also have dramatic effects on indirect water withdrawal and consumption due to PV's very low need for water in its operation.

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How are Micro Enterprises Adopting Emergent Technologies?

Peter Dorrington, Franck Lacan and Samuel Bigot

Abstract This paper presents the results from a survey of emerging and micro SMEs, along with entrepreneurs, creative practitioners, and the new group of 'makers', who are beginning to adopt (or consider adopting) the newer entry-level emergent technologies such as 3D printing. A number of key findings are discussed: including, the prevalence of 'self-taught' users of these technologies; major business activity in the creative industry space; the importance of shared equipment usage by micro organisations in comparison to small companies using external bureau services. Unsurprisingly cost is still cited as a factor for poor uptake of emergent technologies, closely followed by a low awareness of 3D printing and its capabilities, and 3D printing supply chains. Skill levels reported by the participants for each technology highlighted that 3D printing had the most pro-users, which may highlight the increased access to such technologies for micro enterprises, typically reserved for incumbent organisations.

Keywords Micro SME · 3Dprinting · Digital technologies · Emerging technologies

1 Introduction

The Price Waterhouse Coopers (2014) [1] survey noted a lower rate of 3D printing adoption by smaller companies (59 vs 75 %) with Brett et al. suggesting '3D printed product quality', 'lack of expertise' and 'Price' as the main barriers [2]. Romouzzy-Ali et al. confirmed these views [3], also citing "Reluctance to change" as a main barrier. These studies all concentrate on Small and Medium Enterprises,

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and the adoption of digital manufacturing technologies by micro companies is not well documented.

The survey presented in this paper was part of a collaborative research project, called 'Micro Enterprise and Emergent Technologies Laboratory' (MEET Lab). The aim of this research project was 'to investigate the gap between the capabilities of emerging digital technologies and their uptake by micro SMEs and entrepreneurs, focussing on their integration into current business practice'. Similar to larger organisations, these smaller enterprises are drawn to the use of emergent technologies in order to increase their economic viability and sustainability. This project brought together the expertise from a FabLab with a Product Design Research Centre and an Engineering School.

A key objective of the project was to understand what the current needs are of potential users of emergent technologies, as well as how knowledge transfer and Makerspaces are able to assist in addressing such needs, and contribute in democratising the production of social manufacturing.

2 Methodology

A self-completion online survey was used to gather data on micro enterprises adopting emergent technologies. This survey included entry-level 3D printing technologies—a rapidly growing emergent technology—in order to further understand the applications, issues, drivers, and opportunities faced when adopting such technologies. The sampling method was purposive; that is, an interactive process carried out by a researcher when directing their data generation, analysis, theory and sampling activities [4]. For this project, a purposive sample of individual makers, creative practitioners and micro enterprises were targeted, either adopting or considering the adoption of emergent technologies. Respondents were targeted in a number of ways:

- Focussed messages in maker forums and 3D print forums on professional social networks such as LinkedIn;
- Emails to existing company databases from the project partner organisations;
- Adverts on the project and partner websites;
- Use of a 'snowballing' question as part of the survey, to recommend potential respondents;
- Face-to-face promotion of the project and survey at innovation events.

In the main, the survey used closed questions to make it easier for participants to complete in a timely manner; potential respondents are often put off when self-completion surveys appear long, and time-consuming, as such they must be kept short [5]. In addition closed questions 'enhance the comparability of answers, making it easier to show the relationship between variables and to make comparisons between respondents or types of respondents' [6]. However, there is a loss of spontaneity in respondents' answers. As such a number of open or 'free-text' questions were asked eliciting more detailed answers.

A range of question types were considered when designing the survey depending upon their suitability for the information required. In the main 'informant factual questions' were used [6] which places the participant in the position of informants rather than respondents answering questions about themselves; for example: 'how does your organisation access 3D printing?' with a list of options. Personal and factual questions were kept to a minimum—such as 'level of education?'—and placed near the end of the survey to be less off-putting.

An electronic survey tool was utilised for data collection for a number of reasons: ease-of-access for the technologically-savvy target sample; ease of data collection and real-time review of data; the ability to show the respondent visually how far they were through the survey using a completion bar, to encourage to them to complete the survey. A prize to win a 3D printed component using one of the processes available from the partner organisations was included to increase participation.

3 Results and Findings

3.1 Survey Respondents

For the purpose of these results individual and micro enterprises are categorised as 'micro organisations'; that is, an entity with 9 or fewer persons. There were 57 surveys considered complete out of the 78 respondents; only these were used in the findings and results section to maintain integrity of the data analysed.

Organisation Type. The survey was purposively sampled to individual and micro companies, i.e. those with 1–9 employees. Response rates for these types of organisations were 50.9 and 35.1 % respectively. In addition, a number of smaller, more established companies responded to the survey (10.5 %) representing organisations with 10–49 employees. These organisations represent 'small' companies, and are referred to as such from herein; only 3.5 % placed themselves in the 'other' category.

Geographic Distribution. The online survey was predominantly aimed at UK respondents, hence the natural bias toward these countries. Due to the use of social media to distribute the survey, a number from outside the UK also completed the survey, and were included for completeness (Fig. 1).

Roles of Participants. A number of roles were reported by participants (51 in total), and free text answers given. Due to the variety of job titles, the answers were consolidated into common descriptions; for example, CEOs (Chief Executive Officers) and Directors both direct, make decisions and lead their company, and were together (Fig. 2).

The majority of respondents were 'Directors' (25.5 %) followed by the group of 'Founder/owners' (19.6 %). Looking at company size, job roles from across the range were reported by makers and micro organisations as either Directors/Founders

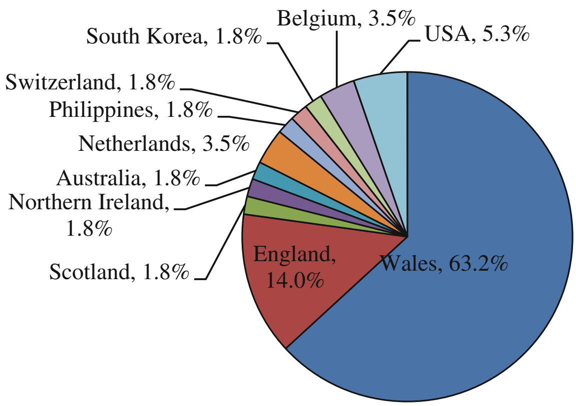


Fig. 1 Location of participants' organisations

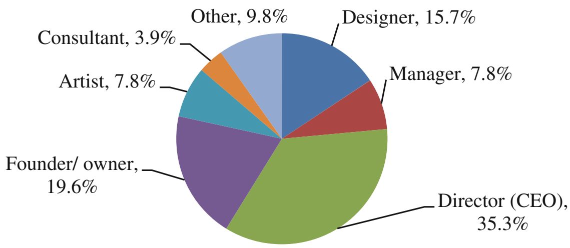


Fig. 2 Roles of participants

or Co-founders; whereas in small companies they were either Managers or Directors (Fig. 3).

Levels of Education/Training for Emergent Technologies. 48 respondents completed the training and education question reporting any education they had received incorporating an element of emergent technology training. 9 skipped the question, all of which were from the independent/creative practitioner category. The majority of respondents have been 'self-taught' (37.5 %) when learning how to use emergent technologies. This may be a reflection on the speed at which these technologies are moving and the importance of learning through 'doing' [7]. The second largest level of training was reported as 'Degree' level (27.1 %),

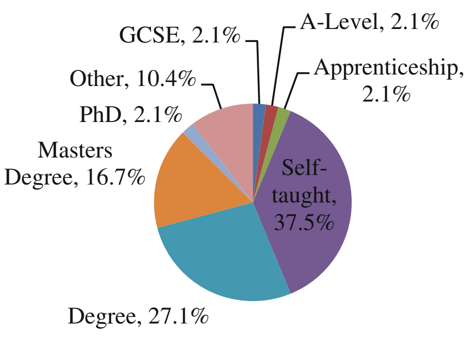


Fig. 3 Highest level of training of respondent

highlighting the increased use of lower-level technologies such as 3D printing and laser cutting as part of the degree process.

Interestingly, the overall results show that a high majority of respondents (62.5 %) have received some form of training or education on digital technologies. The fact that they are adopted by people who already have some background in these technologies rather than people with no previous experience in them tend to suggest a maturation of these technologies rather than a hype.

Learning Requirements. Participants were asked which technologies they would like to learn more about for their business or practice; overall 'scanning' and '3D printing' had the largest demand for learning. 3D printing was expected with the current presence of such technologies in the media, however scanning was a surprise, further evidenced by the increasing number of entry-level scanning technologies now entering the market (e.g. Asus XtionPro, Kinnect, Fuel3D). Handheld scanning technologies have typically expensive to buy (tens of thousands of pounds).

Current Activities of Participants in this Area. The micro enterprises carry out a wide range of activities ranging from marine products, pet products, rehabilitation products through to medieval replica armour and weapons! Activities in the creative industry sector made up the majority of activities of our participants (42.1 %), followed by consumer products (28.1 %). Following these, the responses show a general spread amongst the areas outlined, which displays how these emergent technologies are being trialled for a number of different activities, typical of the exploratory nature of the maker movement.

13.8 % of respondents reported activity in aerospace; 3 out of 7 of these were small companies (10–49 employees); surprisingly the other 5 were micro enterprises. Surprising due to the higher entry barriers of this market and domination by larger organisations, which have the resources to adhere to the demanding quality standards for this sector. The majority of these organisations also included automotive and consumer products as activities they cater for, again highly demanding sectors in terms of meeting exacting quality standards. Some niche markets such as car personalisation and restoration of collectible vehicles could however benefit from these technologies.

3.2 Observations Between Entrepreneurs, Micro-Enterprises and Small Companies

The survey attracted over 10 % of responses from smaller companies, even though the target was initially micro-enterprises. Although fewer of these smaller companies were sampled, they do demonstrate responses from organisations which are more established than those organisations with fewer than 9 employees. As such, they provide a different lens with which to compare and contrast the different uses of emergent technologies. This section discusses some of these findings; albeit, with the caveat that there were fewer small (i.e. 10–49 employees) companies in the survey, so the results cannot be taken as significant.

Note: for some questions the respondent was allowed to select a number of answers, e.g. ‘Which of the following applications do you use digital manufacturing technologies for?’—clearly such a question might have a number of responses for each organisation. As a result, the averages are calculated across responses provided, and do not therefore add up to 100 %.

Activities. The micro organisations are mainly focused on the creative industries, closely followed by consumer products (45.8, 29.2 % respectively). Small companies reported medical as the largest activity, followed by IT and electronics (66.7 and 50 %). The rest of the activities appeared to be equally spread.

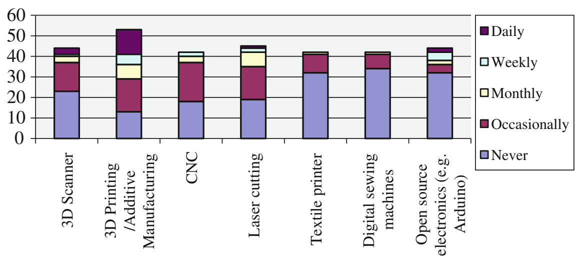
Applications. The key applications of emergent technologies for micro/independent organisations were prototyping (56.3 %), production (54.2 %), artwork and decorative items (52.1 %); small companies reported key applications as prototyping, production and presentation models equally (50 %). Micro organisations appear to be using emergent technologies for production more than smaller, more established companies. This could be due to the series production and use of proven technologies by smaller companies, and the more experimental nature of creative practitioners/micro organisations in experimenting with these technologies. Emergent technologies are also cheaper for micro SMEs to purchase in comparison to the equivalent technologies produced for series manufacture. For example, comparing two systems using SLA: (a) 3DSystems ProJet 6000 series SLA printer can be purchased for 220,000 GBP [8] and (b) whereas the Kudo3D Titan 1 costs 1800 GBP [9].

Clearly (a) is a proven technology and for the professional market, with superior build size, build quality etc. however the shear drop in prices for entry level emergent technologies allows micro enterprises to engage in these technologies.

One observation for smaller companies was that they reported artwork and decorative items (16.7 %) as their lowest application. This follows as such items tend to be one-offs and heavily time consuming; small, more established companies are likely to focus on batch production or mass production in order to benefit from economies of scale in order to sustain the larger number of employees and overheads in their companies.

Accessing Digital Technologies. A surprisingly large number of micro organisations have their own in-house scanning equipment, or have access to shared scanning facilities, in comparison to the small companies, who in the main used service bureaus (refer to Fig. 4). This may be indicative of entrepreneurs testing out

Fig. 4 Frequency of access to emergent technologies



entry-level scanning technologies in micro companies for new applications, compared to small companies who are using higher-end scanners for measurement analysis or reverse engineering.

A noticeable difference between the sub-9 employee organisations and the smaller companies was the increase in the reported use of shared equipment facilities or use of maker networks in comparison to the small organisations using service bureaus. This may be a reflection of the more 'exploratory' innovation carried out by the micro enterprises, who are able to take advantage of the open models of MIT FabLabs [10] which essentially allow users to use the FabLab if they share any knowledge they develop there for other users. Conversely, small companies and more established companies are likely to be bound by non-disclosure agreements or have intellectual property concerns, preventing them from sharing so openly. Of the smaller companies who answered the survey, the least accessed technologies were textile printers, digital sewing machines and open source electronics; a similar pattern was observed with the micro/individual organisations: digital sewing was the least accessed, followed by textile printers and open source electronics. In relation to textile printing and digital sewing, it was felt that the survey may not have reached users of these technologies and showed a slight bias; however, further analysis showed that 9 and 7 out of these technology types, respectively, had used the technologies on occasion. Perhaps the need will increase with the future development of smart fabrics.

3D printing came out as the emergent technology most frequently accessed by all organisations (i.e. on a daily basis). In terms of access, 3D printing was the technology most required for daily access; CNC was the most required for weekly access; and in terms of monthly access the respondents listed 3D printing again. Ultimately the popularity of accessing these technologies is highlighted. It is interesting to note that CNC, although a more established technology, still remains of interest. Participants could well be referring to the lower cost emergent CNC technologies which are now more user-friendly, ideal for one-off products, and small batch runs in the creative industry.

Replacement of Traditional Technologies. 39.4 % of micro organisations reported that the emergent technologies have replaced traditional technologies, in comparison to 33.3 % for small companies. This is likely due to the larger number of creative practitioners in the individual category which has typically used hand-crafting techniques.

Drivers for the Adoption of Emergent Technologies. The largest reported driver for the adoption of emergent technologies was the 'ability to accelerate design iterations, product development and testing' (56.1 %); next highest was 'curiosity' (47.4 %) followed by 'geometric freedom', 'product personalisation' and 'keeping up with technology' equally (43.9 %). Disaggregating individual/micro organisations with small companies displayed no noticeable difference,

Barriers to the Uptake of these Technologies. Figure 5 displays the barriers recorded for the sample. Overall the major barrier to the adoption of emergent digital manufacturing technologies was cost by quite a large margin (78.9 %). The next barriers were 'low awareness of 3D printing and capabilities' and 'access to

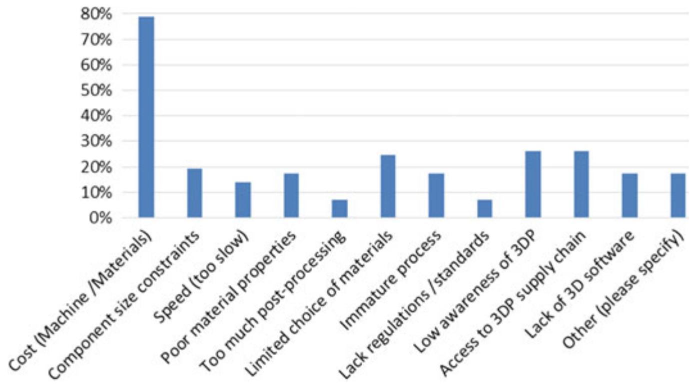


Fig. 5 Barriers to the adoption of emergent digital manufacturing technologies

3D printing supply chains' (26.3 %), with 'a limited choice of materials shortly afterward' (24.6 %); material choice is an interesting barrier, particularly when one of the most frequently used emergent technologies used was that of 3D printing. The majority of 3D printing used by this cohort is highly likely to be that of Fused Deposition Modelling (FDM), where a plethora of low cost plastic materials have now appeared. This perhaps links to the barrier reported of 'low awareness', and the 'lack of access'.

Which Materials would Respondents like to Produce Future Parts from? Micro organisations selected metal (68.8 %) as the most popular future material, followed by plastic (64.6 %) and wood (47.9 %). The result for wood was surprisingly high; it was considered that this might be due to the larger number of artists in this group, and the requirement for the inherent natural aesthetic qualities of wood, along with their experience or handcrafting with wood.

The choice of metal is less surprising, potentially due to the requirement for strength; micro organisations are less likely to access the higher cost RP machines which make use of stronger materials.

Small companies prioritised the materials they would like to use for emergent technologies as: plastic (83.3 %); metal (66.7 %); and textile (50 %). The finding drawn from this could be that they are less likely to need access to metal as they can access higher quality RP technologies, e.g. SLS/nylon materials, versus a micro company using PLA.

Membership of a Maker Group? The authors considered that membership to maker groups would be more prevalent with micro organisations, however a similar percentage for micro and small company respondents was observed: 18.8 and 16.7 % respectively.

Replacement of Traditional Technologies. The results were disaggregated and compared for each of the organisational sizes, and the corresponding answers were similar with approximately one-third saying the technologies had replaced traditional technologies, and two-thirds saying otherwise. 3D printing technologies were

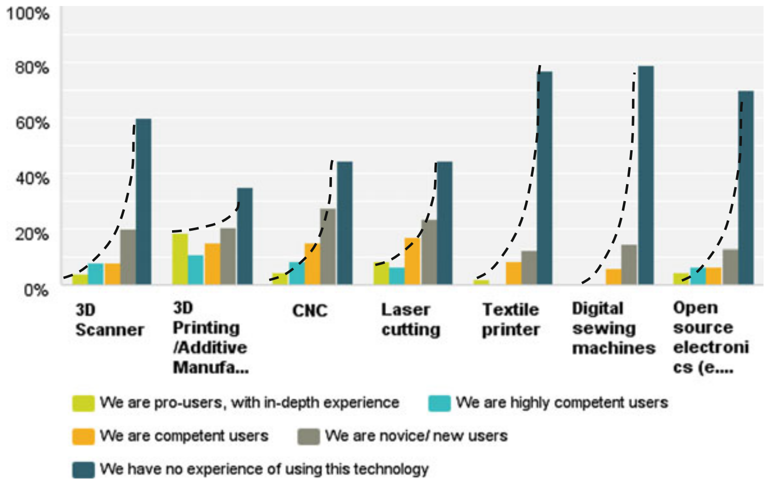


Fig. 6 The level of expertise that is present with each of the listed emergent technologies

reported as being the most frequent replacement technology for traditional technologies. Secondly, digital CNC and laser cutting were reported.

Level of Expertise Present. Figure 6 displays the level of expertise that is present with each of the listed emergent technologies.

A dashed line has been drawn in black showing that for the majority of technologies there are a small number of pro-users increasing gradually as the competency of users reduces to those with no experience. This appears to be a trend for most of the technologies; one might expect there to be fewer people describing themselves as pro-users for the slightly more mature technologies, however for 3DPrinting the level of expertise appears to display more of a level playing field; more people seem to be involved across the board in this technology, possibly a result of its current popularity and hype.

How the Different Technologies were Learnt—Fig. 7 suggests that for the majority of technologies, participants are familiar with more face-to-face learning, however still follow a large amount of trial and error with emergent technologies, particularly with a number of the technologies.

4 Discussion

By offering the possibility to almost anyone to produce components almost anywhere, 3D printing is transferring the value of an object to its digital design [11]. Our collaboration with micro SMEs throughout this project has highlighted that the adoption of 3D CAD modelling was a significant bottleneck to the adoption of digital technologies. To date, the acquisition of 3D CAD software with professional capabilities is seen as a very expensive investment for small businesses and,

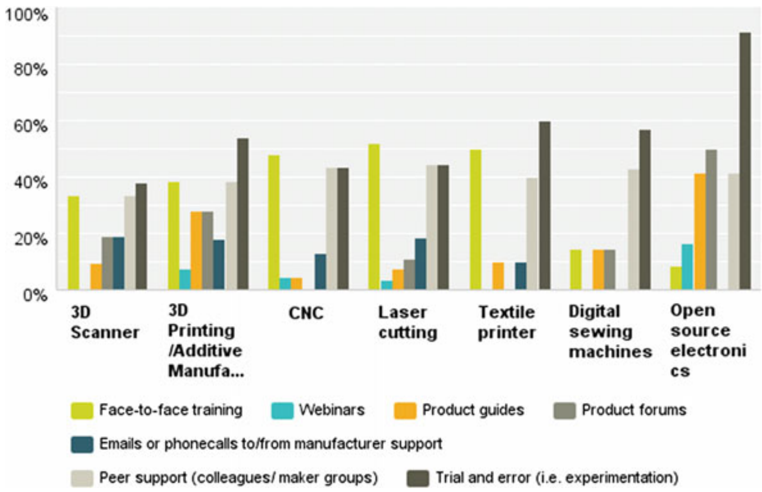


Fig. 7 The way in which participants learnt to use the technologies

additionally, such software has a long learning curve. The 'hype around home use obfuscates the reality that 3D printing involves a complex ecosystem of software, hardware and materials whose use is not as simple to use as 'hitting print' on a paper printer' [12]. Contrary to low cost 3D printing, there currently appears to be no low cost 3D CAD software equivalent. As a result, it is believed that micro companies are looking at 3D scanning as a low cost alternative to digitise their products. However, the low cost 3D scanning devices tested by the authors do not currently offer the level of details and accuracy required by most mechanical applications. Furthermore, the files produced by these low cost systems can prove difficult to amend and import into traditional CAD software. There is also the issue of Intellectual Property when scanning for reverse-engineering applications; for example, a hot topic of discussion at the recent 3DPrintShow in London [13] was that of breaching Intellectual Property of consumer products.

The survey results suggest that there is a need for 3D printers to produce components in materials with higher mechanical properties, such as metal. Currently, the price and complexity of metal additive manufacturing processes make such machines very unlikely to appear soon in a micro SME's workshop, however, with the recent expiration of key patents, more affordable 3D printing machines based on other technologies such as SLA and SLS principles are emerging, and allow for the production of parts with enhanced properties.

Our survey demonstrates a wide range of application areas for emergent technologies, with the majority being focused around the creative industry (42.1 %) followed by consumer products (28.1 %). The former is likely to be slightly biased due to the purposive sampling of the survey, focusing on creative practitioners, individuals and micro enterprises, which appear to still be experimenting with the best ways of applying these technologies. Furthermore the results may indicate that people are being attracted from niche markets who see emergent technologies as an economical enabler for product development.

With the democratisation of digital technologies, affordable machines can easily be purchased on the internet. Despite online help and forums, low cost 3D printers can, from experience, prove difficult to run reliably. A main finding of this survey is that the most frequent level of training received was through 'self-taught' processes, followed by degree courses. The rapid entrance of new products into the market and the experimental nature of the technologies adds to this need for self-learning and 'hacking' of technologies as individuals explore what they can do with them.

5 Conclusion

A number of key findings have been drawn from this initial survey; including: the prevalence of 'self-taught' users of emergent technologies; the major business activity of the micro enterprises and small companies surveyed being in the creative industry space; and the importance of shared equipment usage by micro organisations in comparison to small companies using external bureau services.

The creative industry is considered more open to the Makerspaces' and FabLabs' co-creation philosophy than the more conservative manufacturing industry. Each Makerspace is unique with objectives driven by their members (community development, education, incubator or co-working spaces…). Understandably, some micro companies can be reluctant to share their innovative ideas, however, such flexibles and creative environments provide access to a vast range of technical skills and knowledge across various fields and domains. They also encourage the development of problem solving methods [14] and push people into acting rather than behaving, thus adopting an active attitudes towards the technology [15].

Unsurprisingly cost is still cited as a factor for poor uptake of emergent technologies; closely followed by a low awareness of 3D printing and capabilities and 3D printing supply chains.

Of particular interest were the curves showing the level of skill reported by the participants for each technology; most technologies displayed a small number of pro-users increasing to larger numbers of novice users; however, for 3D printers the numbers of participants classing themselves as pro-users was larger, with similar numbers reported across all categories of skill. This may be an indication of the speed at which desk-based 3D printing has penetrated the micro organisations as well as the more established companies with 10–49 staffs.

This survey provides an initial snapshot of how the lesser researched micro enterprises and micro SMEs are adopting emergent technologies. The authors accept the limited geographical focus of this survey, and findings are early indicators only, however they provide useful insights gained from early adopters of technologies which were traditionally only available to larger companies.

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Improving Performance of Eco-Industrial Parks

Bert Bras, Astrid Layton and Marc Weissburg

Abstract Industrial Ecology hypothesizes that networks of industries designed to be analogous to the structure and properties of food webs may approach a similarly sustainable and efficient state. Although ecology is the metaphor for designing Eco-Industrial Parks (EIPs), prior research has shown that IEPs are inferior in performance compared to natural ecosystems. One EIP design approach is to enlarge EIPs by combining two or more synergistic networks to create a larger, and hopefully more successful, synergistic mega-network. An quantitative analysis using ecosystem metrics is presented in this paper in order to test the potential of this approach.

Keywords Industrial ecology · Ecosystems · Design · Manufacturing

1 Introduction

Many believe that the environmental problems from our production systems are not solvable by a “silver bullet” technology [1], but that a systems-based solutions is needed. In order to achieve true sustainable manufacturing, a systems view that goes beyond a single factory and company is needed. Close collaboration between multiple companies and stakeholders around internal and external value chains and resource networks have to be pursued in order to move from the current “take-make-waste” society to a truly cyclical production paradigm.

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Fundamental insight for such sustainable manufacturing systems can be obtained from Nature where ecological systems are examples of sustainable systems. Ecological food webs and interacting industries both represent collections of entities (species and industries respectively) that exchange materials and energy [2]. Analogous to close and often long-term interactions between two or more biological species, industrial symbiosis occurs when multiple firms or facilities achieve higher system efficiency through the exchange of 'waste' energy and materials. An eco-industrial park (EIP) is characteristic of a type of industrial symbiosis that occurs among firms co-located in a bounded geographic area, typically an industrial park, where industries share and/or exchange inputs and outputs (for example raw materials, products, process wastes, or water) as an industrial ecosystem [3]. A commonly cited EIP example is Kalundborg, Denmark [4]. Companies in an IEP can form a resource exchange structure analogous to a natural food web.

A central hypothesis in the field of Industrial Ecology is that such a network of industries will approach a similarly sustainable and efficient state as a natural ecosystem [5]. In general, however, ecological principles have been used more as qualitative metaphors for EIP design than as a source for sound design principles [6–8]. Ecology, however, has the potential to offer much deeper insight and science-based understanding of symbiotic systems. For example, as detailed in Sect. 2 of this paper, ecological literature defines metrics that examine ecosystem properties and species interactions and ecologists use structural measures and metrics for the analysis of ecological food webs [9–13]. Interspecies interactions within these complex networks are graphically organized into food web diagrams that capture biodiversity, species interactions (particularly feeding relationships), and the structure of links (e.g. between predators and prey). Metrics developed by ecologists describe and analyze the structures governing food webs, properties of which are highly desirable in industrial systems and may be transferred by mimicking the food web structure. For example, a carpet recycling network designed using structural food web metrics was found to positively correlate ($R^2 = 0.96$) with standard cost- and emissions-minimizing designs [14]. Principles and metrics for assessing ecosystem robustness and stability seem also relevant and applicable to improving sustainability of industrial systems [15].

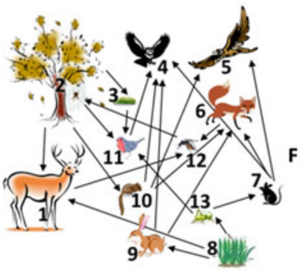
In [16], building upon the quantitative knowledge in ecology, the structures of eco-industrial parks (EIPs) were compared to food webs using a variety of important structural ecological parameters discussed in detail in Sect. 2. This comparison used a comprehensive dataset of 144 natural food webs that provided a more ecologically correct understanding of how food webs are organized than previous efforts. As shown in [16], the 48 EIPs showed an average and maximum performance well below the average performance characteristic of food webs. For example, the "best" EIP in the collection has a cyclicity of 3.87 and a linkage density of 3.13 while the average natural food web has a cyclicity of 6.03 and a link density of 7.69, almost twice as large as the two values for the best EIP. This raises an interesting design and research question: "*How can we improve these values and associated performance of EIPs?*"

Identifying fundamental physical relationships responsible for the correlation between bio-inspired network patterns and environmentally superior industrial network designs and create design guidance there from are long term goals of our research. One EIP design approach to increase the success of EIPs is to enlarge EIPs by combining two or more synergistic networks to create a larger, and hopefully more successful, synergistic mega-network. An initial analysis of this approach is presented in this paper to test the potential of this approach. First, however, some background on ecosystem metrics is provided.

2 Structural Ecosystem Metrics

Ecological literature defines metrics that examine ecosystem properties and species interactions (see, e.g., [10, 12, 17–21]). The flows of materials and energy in an ecosystem and its food web can be represented in a food web matrix [**F**]. The interactions are organized between predators (columns, resources flow to predators) and prey (rows, resources flow from prey). Figure 1 shows a hypothetical food web represented as a directional digraph (left) and converted into a food web matrix (right). Since a species (N) can be both predator and prey the result is a square matrix. A value of 1 indicates the existence of a directional flow from row to column and a zero indicates no connection. In other words, if predator-j feeds on prey-i, then $f_{ij} = 1$; the interaction (or link, L) is accounted for exactly once in the food web matrix. The maximum number of links, L scales as $(N) * (N - 1)$ if cannibalism is not allowed and N^2 if it is (noted as a 1 on the diagonal).

A wide variety of metrics have been developed to understand the link between structure and behavior of ecological systems [22, 23]. The structural measures and metrics used most frequently by ecologists can be calculated using the



F = (prey × predators)

prey \ predators	1	2	3	4	5	6	7	8	9	10	11	12	13
1	0	0	0	0	0	0	0	0	0	0	0	1	0
2	1	0	1	0	0	0	0	0	0	1	1	0	0
3	0	0	0	0	0	0	0	0	0	0	1	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	1	0
7	0	0	0	1	1	1	0	0	0	0	0	0	0
8	1	0	0	0	0	0	0	0	1	0	0	0	1
9	0	0	0	1	0	1	0	0	0	0	0	0	0
10	0	0	0	1	1	1	0	0	0	0	0	0	0
11	0	0	0	1	0	0	0	0	0	0	0	0	0
12	0	1	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	1	0	0	0	1	0	0

Fig. 1 *Left*—A food web of a hypothetical ecosystem with species numbered. *Right*—A food web matrix; $f_{ij} = 1$ represents a unidirectional link between prey (i) and predator (j) and a zero represents no link

$N \times N$ structural food web matrix shown in Fig. 1. These metrics can be calculated knowing only structural information, that is, all calculations per Eqs. 3–13 are simply based on binary information on whether a link exists between two actors in the matrix, or not. f_{ij} represents the linkage between actor i to actor j and is the ith row and jth column entry in the matrix with a value of either 1 (link exists) or 0 (no link). Linkage density (L_D) is the number of links in the system normalized by the number of actors in the system [24]. The number of prey and predators (n_{prey} and $n_{predator}$) are the number of actors that provide and consume a resource respectively [12], or producers and consumers in industry terms, respectively. The ratio of these two is the prey to predator ratio (P_R) a numerical representation of the balance of consumers to producers in the system. The number of specialized predators ($n_{S\text{-}predator}$) is a subset of $n_{predator}$ and only counts those consumers who interact with only one actor. The specialized predator ratio (P_S) is the fraction of consumers that are specialized. Generalization and vulnerability (G and V) are subsets of L_D and represent respectively, the number of producers that a consuming-actor can consume and the number of consumers a producing-actor provides flows to [12, 18]. Connectance (C) is the number of realized direct interactions in a web divided by the total number of possible interactions. If one forbids cannibalism, then the denominator is the fraction of nonzero off diagonal elements in the foodweb matrix [**F**]. Cyclicity (λ_{max}) is the maximum real eigenvalue of the transpose of the food web structural matrix (flow is columns to rows). Cyclicity represents the presence and complexity of internal cycling in the system [22, 25–27], and is taken as an indication of how cyclic pathways proliferate as the number of steps in the cycle grows. More detailed descriptions of these metrics may be found in [16] in addition to the references already listed.

$$L_D = L/N \tag{1}$$

$$f_{row}(i) = \begin{cases} 1 & for \sum_{j=1}^{n} f_{ij} > 0 \\ 0 & for \sum_{j=1}^{n} f_{ij} = 0 \end{cases} \tag{2}$$

$$n_{prey} = \sum_{i=1}^{m} f_{row}(i) \tag{3}$$

$$f_{col}(j) = \begin{cases} 1 & for \sum_{i=1}^{m} f_{ij} > 0 \\ 0 & for \sum_{i=1}^{m} f_{ij} = 0 \end{cases} \tag{4}$$

$$n_{predator} = \sum_{j=1}^{n} f_{col}(j) \tag{5}$$

$$P_R = n_{prey}/n_{predator} \tag{6}$$

$$f_{s-col}(j) = \begin{cases} 1 & for \sum_{i=1}^{m} f_{ij} = 1 \\ 0 & for \sum_{i=1}^{m} f_{ij} \neq 1 \end{cases} \tag{7}$$

$$n_{S-predator} = \sum_{j=1}^{n} f_{s-col}(j) \tag{8}$$

$$P_S = n_{S-predator}/n_{predator} \tag{9}$$

$$G = L/n_{predator} \tag{10}$$

$$V = L/n_{prey} \tag{11}$$

$$C = L/N^2 \tag{12}$$

$$\lambda_{max} = max, real\, eigenvalue\, solution\, to : 0 = \det(\boldsymbol{A} - \lambda \boldsymbol{I}) \tag{13}$$

3 Combining Eco-Industrial Parks

In [16], the 48 EIPs analyzed showed performances well below the average performance characteristics of food webs. A quick response to increase the performance would be to increase the size of the EIPs ("more is better"). In the following, several EIPs were chosen and grouped together based on shared materials and energy exchanges. These groupings are theoretical because these EIPs are not co-located and material exchanges would have to occur over great distances in practice. Linkages inside each of the EIPs were not modified. All possible links were added between EIPs based on knowledge of what was being exchanged in the original EIP. This results in a maximally connected combination-EIP. Ecological metrics were calculated for each of the groups and compared to the values of the individual EIPs in each group. The metrics were also calculated for the grouped EIPs before new connections were added to highlight the effect of the new connections. Diagrams of each EIP can be found in the supplemental material of [16] and are not repeated here.

3.1 EIP Combo 1: Lubei Industrial Park, Mongstad EIP, Wallingford EIP, and Kymi EIP

The four EIPs in *Combo 1* were paired due to a common use of water, steam, fly ash, wastewater, electricity, hydrogen, carbon dioxide, chlorine, and sodium hydroxide. Lubei Industrial Park, designed to be located in China, is outlined in [28]. The Kymi EIP located in Kymenlaakso, Finland is outlined in [29]. Both the Wallingford EIP in Wallingford, Connecticut and the EIP Mongstad in Mongstad, Norway are outlined in [30]. The Lubei and Mongstad EIPs both have aquaculture as their active agriculture actor. Nine different materials and energy streams can be exchanged between the four EIPs if they were co-located, but considering distances between the EIPs only five flows can realistically be exchanged (Table 1).

3.2 EIP Combo 2: GERIPA, Gladstone, and Montfort

The three EIPs in *Combo 2* were paired due to a common use of soil and other organic wastes, fly ash, and biogas. GERIPA, which stands for Geração de Energia Renovável Integrada á Produção de Alimentos, is an IBS (integrated bio-system) designed for Brazil and is outlined in [30, 31]. Gladstone is a proposed addition to an existing EIP in Gladstone, Australia and is outlined in [30, 32, 33]. The Montfort Boys Town is also an integrated bio-system located in Suva, Fiji and can be found in [30]. The active agriculture actors in the three EIPs GERIPA, Gladstone, and Monfort include respectively farming and a biodigestor, biomass and fertilizer production, and farming, aquaculture, and fertilizer production. Six different materials and energy streams were able to be exchanged between the three EIPs, four of which realistically could be exchanged taking into account the distances between the EIPs (Table 2).

3.3 EIP Combo 3: Brownsville EIP, Burnside EIP, Clark Special Economic Zone, and Kawasaki

The four EIPs in *Combo 3* were paired due to a common use of soil and other organic wastes, waste plastic, used oil and tires, steam, water, and wastewater. The Brownsville EIP was located in Brownsville, TX and is outlined in [34]. The Burnside EIP is in Nova Scotia, Canada and can be found in [35]. The Clark Special Economic Zone was proposed for the Philippines [30]. The active agriculture actors in the Clark EIP are the result of landscaping, a golf course, a greenhouse, and composting. Seven different materials and energy streams were able to be exchanged between the four EIPs, four of which realistically could be exchanged taking into account the distances between the EIPs (locations range from Texas to

Table 1 Combo 1 EIP made up of Kymi EIP, Lubei Industrial Park, Mongstad EIP, and Wallingford EIP

EIP *Combo 1*	Active Agriculture component?	Actors (N)	Links (L)	Predator	Prey	Connectance ($C = L/N^2$)	Linkage density (L_D)	Prey/predator ratio (P_R)	Specialized predator fraction (P_S)	Vulnerability (V)	Generalization (G)	Cyclicity (λ_{max})
Kymi EIP	N	8	14	7	7	0.22	1.75	1.00	0.714	2.00	2.13	1.82
Lubei Industrial park	Y	9	17	7	8	0.21	1.89	1.14	0.429	2.13	2.22	0
Mongstad EIP	Y	11	20	10	8	0.17	1.82	0.8	0.300	2.50	1.57	1.55
Wallingford EIP	N	12	18	11	9	0.125	1.50	0.820	0.545	2.00	2.80	1
Combo 1 pre links added		40	72	35	32	0.045	**1.80**	**0.914**	**0.486**	**2.25**	**2.06**	**1.82**
Combo 1 post links added		40	169	36	33	0.106	**4.23**	**0.917**	**0.111**	**5.12**	**4.69**	**4.48**
% change		0	135	3	3	135	**135**	**0**	**−77**	**128**	**128**	**146**

Table 2 Combo *2* EIP is made up of GERIPA, Gladstone, and Montfort IBS

EIP *Combo 2*	Active agriculture component?	Actors (N)	Links (L)	Predator	Prey	Connectance ($C = L/N^2$)	Linkage density (L_D)	Prey/predator ratio (P_R)	Specialized predator fraction (P_S)	Vulnerability (V)	Generalization (G)	Cyclicity (λ_{max})
GERIPA IBS	Y	8	15	6	8	0.230	1.88	1.33	0.167	1.88	1.80	1.93
Gladstone (2008)	Y	23	25	13	14	0.050	1.09	1.08	0.692	1.79	1.17	0
Monfort boys town	Y	9	11	7	7	0.140	1.22	1.00	0.571	1.57	2.43	1
Combo 2 pre links added		40	49	28	26	0.031	**1.23**	**0.929**	**0.607**	**1.88**	**1.75**	**1.93**
Combo 2 post links added		40	124	32	29	0.078	**3.10**	**0.906**	**0.344**	**4.28**	**3.88**	**4.01**
% change		0	153	14	12	153	**153**	**−2**	**−43**	**127**	**121**	**108**

Canada to the Philippines to Japan). Info on the Kawasaki EIP can be found in [28, 36] (Table 3).

4 Discussion

The effect of the additional linkages between EIPs was consistently strongest for the metrics linkage density (L_D), generalization (G), and vulnerability (V). All three of these metrics are influenced by the number of linkages in the network and thus the effect of the addition of linkages is reflected in all of these. *Combo 1* and *Combo 2* saw the biggest increases in cyclicity due to the additional connections made; a 146 and 108 % change respectively. Whether or not it is a coincident, these two groupings also had the largest percentage of EIPs with an agricultural component. The additional linkages did not effect, or had very limited effect on the number of predator- or prey-type actors in the system. This is because we could only use companies that already provided preset materials or energy (prey) and could only connect them to companies that already used preset material or energy (predator). The descriptions of Brownsville, Kymi, Gladstone 2008, GERIPA, Montfort, and Wallingford all contained additional information with regards to what they were exchanging and receiving. This enabled the (hypothetical) creation of new linkages and making actors that were only prey previously now predators too, and vice versa. Without detailed information about the EIPs' input and output flows such new predator- and prey-type actors cannot be designated.

Combo 1 and *Combo 2* both have a drastically higher cyclicity, 4.48 and 4.01 as presented in Table 4 than seen in each of the individual EIPs components. This cyclicity is representative of complex and abundant internal cycles forming between the actors. The average cyclicity seen for food webs is 6.03 and the best EIP in the group of 48 in [16] had a cyclicity of only 3.87. The cyclicities of the individual EIPs making up each combination ranged from zero, meaning no cycles are present, to less than 2, meaning some complex cycling is present. So by combining EIPs together, more connections were able to be made, resulting in a network with a more complex structure. The metrics linkage density (L_D), connectance (c), generalization (G), and vulnerability (V) also showed an increase between the individual EIPs and the combined EIP networks. All four mimicked changes in the number of additional links very closely. For the metrics generalization and vulnerability this was due to the fact that because the information to create new predator- and prey-type actors was not available only the numerators of these metrics changed: the number of links (L). The prey to predator ratio (P_R) stayed approximately the same for all combination EIPs created for the same reason. Linkage density and connectance only changed by the number of links as well.

The changes between the combined EIPs without additional links added, or where the networks are essentially just added together as is, and the combined EIPs with possible links added may be summarized by just two metrics: linkage density and cyclicity. Linkage density captures the number of species in the system and any

Table 3 The *Combo 3* EIP is made up of the Brownsville EIP, Burnside EIP, Clark Special Economic Zone, and Kawasaki

EIP *Combo 3*	Active agriculture component?	Actors (N)	Links (L)	Predator	Prey	Connectance ($C = L/N^2$)	Linkage density (L_D)	Prey/predator ratio (P_R)	Specialized predator fraction (P_S)	Vulnerability (V)	Generalization (G)	Cyclicity (λ_{max})
Brownsville EIP	N	16	22	10	12	0.086	1.38	1.20	0.400	1.83	1.14	1.41
Burnside EIP	N	11	20	10	9	0.165	1.82	0.90	0.300	2.22	2.20	2.05
Clark special zone	Y	20	51	19	17	0.128	2.55	0.90	0.263	3.00	2.00	3.34
Kawasaki	N	8	16	8	8	0.250	2.00	1.00	0.500	2.00	1.62	1.88
Combo 3 pre links added		55	109	47	46	0.036	**1.98**	**0.979**	**0.340**	**2.37**	**2.32**	**3.34**
Combo 3 post links added		55	235	47	46	0.078	**4.27**	**0.979**	**0.149**	**5.11**	**5.00**	**3.94**
% change		0	116	0	0	116	**116**	**0**	**−56**	**116**	**116**	**18**

Table 4 Combination EIPs compared against averages for food webs dataset

	Cyclicity (λ_{max})	Linkage density (L_D)	Prey/predator ratio (P_R)	Specialized predator fraction (P_S)	Vulnerability (V)	Generalization (G)	Actors (N)	Links (L)	Predator	Prey	Connectance ($C = L/N^2$)
Food web averages [16]	**6.03**	**7.69**	**1.13**	**0.100**	**8.82**	**9.69**	**57**	**523**	**47**	**51**	**0.155**
Combo 1	4.48	4.23	0.917	0.111	5.12	4.69	40	169	36	33	0.106
Combo 2	4.01	3.10	0.906	0.344	4.28	3.88	40	124	32	29	0.078
Combo 3	3.94	4.27	0.979	0.149	5.11	5.00	55	235	47	46	0.078

changes in the number of linkages. Cyclicity on the other hand captures any changes in the network structure due to how the new or lost linkages interact with the rest of the system. Connectance could be used interchangeably with linkage density as they both capture changes in actors and links. Linkage density is preferably to connectance however in that it does not require systems of similar size if used for comparisons. Natural ecosystems have far more actors than the IEPs. The prey to predator ratio, generalization, and vulnerability are of interest only if additional information about the system is available so that changes in the behavior of the actors may be made.

5 Conclusion

This paper demonstrates that increasing the size of EIPs helps but is potentially not enough by itself to generate positive food web changes. Changes should result from additional linkages being added, so reducing the size of a network while increasing links would be more positive than simply adding actors to the system without regard to the potential opportunities for exchanges. It has been noted in ecological literature that there may in fact exist a point where a more streamlined network, essentially a network with less diversity, has negative repercussions in the form of overdependence and reduced robustness to random perturbations. A hypothesis within ecology is that diversity may be a strong contributor to the stability of a system: when one actor is removed the system may adapt or recover by another actor(s) stepping into fulfil the supporting role [37]. The natural tendencies for ecosystems as they mature is for the interactions to become more selective, shifting the focus from production towards efficiency [17]. Mature ecosystems obtain efficiency by way of an increase in use of existing actors, essentially using what is available as completely as possible. This results in the desirable property of a complex structure with an abundance of connections between species [22]. These lessons from ecology could support design of IEPs that function truly like ecosystems.

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Product Change Management and Future Information Architectures

Ashley Morris, Rossi Setchi and Paul Prickett

Abstract Implementing and managing the consequences of design change in the context of complex products is challenging. Design changes generate significant volumes of information and product management is becoming increasingly information intensive. It is now critically important that information and communication technology solutions are engineered to support through life product design management processes and the management models used to guide decision making. The purpose of this paper is to describe the prominent challenges of providing through life product management and the nature of information architectures needed to enable efficiency improvements. Actions that need to be taken to make progress are proposed.

Keywords Product · Change · Management · Industry lifecycle · Paradigm · Enterprise · Information · Integration · Interoperability · Supply chain

1 Introduction

1.1 Through Life Product Management

To remain competitive organisations are under continuous pressure to support greater levels of product variation with increasing agility. Consequently the designs of complex products continually evolve. Changes occur at the time of manufacture and within their operating lives, during which they are typically managed in multi-stakeholder environments where many activities have been outsourced.

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The performance and safe operation of complex products are priority design considerations and invariably a high degree of regulatory compliance is required. To ensure that design integrity is maintained there is a need for many stakeholders to coherently reference information relating to design changes.

These issues illustrate that the efficient management of through life support is information intensive and critical to achieving competitiveness improvements. As the result of a growing recognition of the vulnerability of our planet, the need for greater competitiveness must be considered from a more circumspect perspective that places a pure focus on industrial performance in the context of environmental and social needs [1]. To reduce process times, together with labour and material costs, increasingly requires investment in information technology. Unfortunately, current information architectures are based on a "point solution" approach where applications are implemented to support specific functional areas of a business such as design, maintenance, manufacturing and operations. One example of the impact of the current situation is that people spend significant amounts of time searching for the information they need for their work, which can include product design, finance, manufacturing, inventory management, operation and maintenance. The time spent searching for information could be reduced if product information were able to flow more easily across organisations and made more accessible to all who needed it.

1.2 Information Technology Challenges

The volume of data generated is growing as a function of the increasing levels of product variation and the use of embedded software. At the same time the Information Revolution and related phenomena such as the Internet of Things, Industrie 4.0 and the rapid growth of information volumes often referred to as the concept of "Big Data" are enabling enormous changes in the way industries operate. Greater network connectivity enables easier delivery of software up-dates, product monitoring and performance "self-reporting".

One of the barriers to progress is that the software applications used to support each of the enterprise functional areas (design, manufacturing, operation, maintenance and so on) uses slightly different terminology (taxonomy) and database structure (ontology). As a consequence, the rich fully featured enterprise information flows that are required to make efficiency improvements remain out of reach. Furthermore, the lack of close semantic alignment between different software products makes it difficult to reduce the time and costs of implementing enterprise software systems.

These issues collectively represent a significant and complex, pan industry level, information management challenge. This paper will explore some aspects of this topic with a view to presenting some ideas on the product information architectures likely to be required to make improvements to through life product management.

2 Motivation for Research

2.1 Industry Life Cycles

Innovation generates ideas and knowledge that stimulates the creation of new products and as a result new markets emerge. The importance of maintaining a clear understanding about the role that products play in industry life cycles is illustrated by the fact that some believe there is a direct "mirror" relationship between the structure of economies and the products produced [2]. Existing markets respond to innovation by developing more efficient ways to operate. Markets that are unable to change fail and die. The four stages in a market's life are birth, growth, maturity and eventually decline [3]. The process of change is invariably complex, challenging and often requires intervention to overcome any barriers to the guiding force of Adam Smith's "invisible hand". To enable continued and sustainable market evolution some kind of intervention is likely to be required such as the development of new legislation, regulations or standards.

It has been suggested that companies have increasingly outsourced between 70 and 80 % of their manufacturing capability [4] and have sought to shift the focus of their operations to meet the demands of aftermarket through life services. At the same time product operators have sought to outsource maintenance and support activities.

The challenge of delivering through life product management is thus exacerbated by the fact that the product change process spans many organisations in the supply chain. The process of maintaining and monitoring design integrity requires the collaboration of a number of stakeholders that include those bodies responsible for ensuring regulatory compliance. The design management and change control methods used in the past, are unsuited to the complexities of today and product change management practices therefore need to evolve [5–7]. To make improvements there is a need to more closely align through life design management processes, information technology and the management models used to guide decision making.

2.2 Management Models

In the context of industry life cycles it is useful to consider the impact of innovation and product change from the perspective of corporate life spans. The average life expectancy of a large organisation of Fortune 500 or equivalent size seems to range between 30 and 50 years. Analysis of the factors that limit organisational life indicate there is an inability or unwillingness of the leaders and managers to adapt the way they think about their companies in relation to markets and competitor challenges. As a consequence many organisations eventually realise that they are no longer operating in the market that they thought they were. The management decision-making models that evolved to support successful operations, are often difficult to adapt to industry changes and so businesses decline [8, 9]. This issue is often considered in the context of organisational development or learning.

The concept of a management decision-making model essentially describes an integrated set of ideas and practices that shape the way people view and interact with the world. This collection of ideas represents a mental model. When a group of people adopt a common “mental model” it might appear as an organisational culture or management “paradigm” [10, 11].

Two prominent management paradigms currently used to consider the flow of products and product related information and services are “Product Lifecycle Management” (PLM) and “Supply Chain Management” (SCM). PLM describes a product management approach that would address the issue of managing processes that span many organisations, yet its benefits have not been realised. This could be due to a lack of clarity that arises because “PLM” also describes a category of software application that is used to manage product design information [12]. SCM is another model that supports improved product flow through supply chains. It emerged in the 1980s—coincidental with the emergence of Enterprise Resource Planning (ERP) technology [13]. SCM is a model that describes a need for closer integration of processes that span product design, manufacture, operation and maintenance. Despite widespread recognition of the benefits to be achieved little progress has been made over the last two to three decades. This could be due to a lack of agreement of what the SCM concept stands for [14, 15].

2.3 Product Management

The safety and performance of high-value, long-life products are often priority design considerations and so regulatory involvement in the design process is required. Since the knowledge and organisational capabilities required to design and manufacture complex products cannot be replicated easily, product operators and maintainers often rely on the original equipment manufacturer (OEM) for through life product support. As a consequence the design change process spans multiple organisations and to ensure that design integrity is sustained there is an enduring need for manufacturers, operators and maintainers to collaborate. This arrangement has been complicated by the growth of the service economy and the trend to outsource the provision of maintenance and manufacturing capabilities [4]. Thus while the ultimate responsibility for the safe design and operation of complex products rests with operators and OEMs there is a significant increase in reliance on suppliers to support the management and incorporation of design changes.

These issues are compounded by the fact that the designs of complex products are all different. When products are managed as fleets, the slight design variation between each of the products that is evident shortly after manufacture gradually increases due to the cumulative impact of through life design change. As a consequence the designs of the products in a fleet can be seen to diverge as the fleet ages [16]. Additional product management challenges that should be considered include: the increases to product variation that arise from the need to design products that are more precisely matched to customer requirements; the increasing use of embedded software; the need to improve the audit ability of parts' manufacturing and maintenance histories; and, to support greater sustainability, the growing responsibility being placed on manufacturers to manage the product end-of-life reuse, disposal and recycling. These factors are creating a significant increase in the volume and importance of information and knowledge.

2.4 Information Technology

Significant volumes of information are generated during product development which is then embedded within catalogues, bills of materials, inventory, assembly, test, operation and maintenance instructions. Whenever a design is modified, there is a need to communicate relevant information to customers and suppliers. An additional complication is that the modification process creates numerous versions of the same product. While OEMs typically have a structured approach to managing the internal product design change process, many experience real challenges when coordinating and communicating change information to support their businesses and customers. This process is supported by a variety of software applications that are implemented to support the prominent process areas, or focus points. To improve through life product management, there is a need to improve the way information systems support the product change process. Improved software application interoperability is an important priority [17]. This will require a departure from the current "point solution" architecture approach where applications are implemented to support specific functional areas of a business such as design, maintenance, manufacturing and operations. The current approach requires users to enter product information directly into individual systems, with little control as to the quality of that information [14, 18].

These issues would be resolved if product information could flow more easily across organisations and be accessed by all who needed it. Unfortunately, one of the barriers to progress is that the software applications used to support each of the enterprise functional areas (design, manufacturing, operation, maintenance and so on) use slightly different terminology (taxonomy) and database structures (ontology). As a consequence, the rich fully featured enterprise information flows that are required to make efficiency improvements remain out of reach. To overcome the lack of close semantic alignment between different software products requires data mapping and integration activity that increases the time and costs of implementing enterprise software systems.

3 Investigative Approach

To investigate how the closer alignment between through life design management processes, information technology and the management models used to guide decision making, the research approach illustrated in Fig. 1 has been adopted.

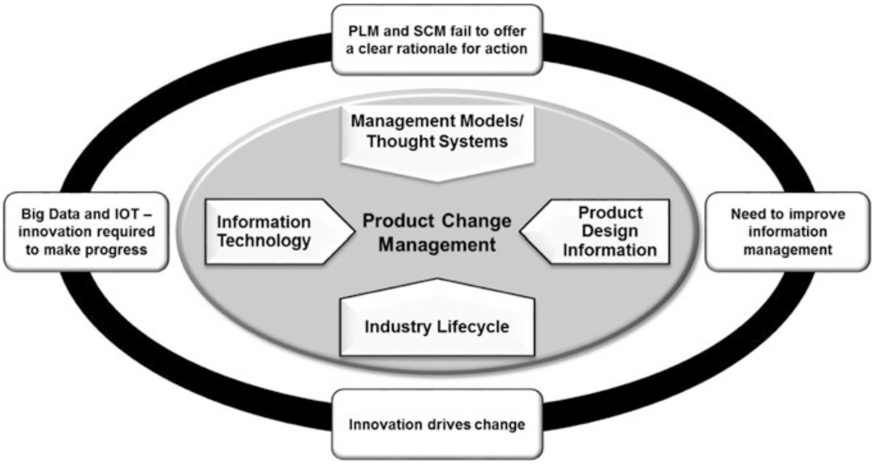

Fig. 1 Research approach

This considers the issue of managing product change in the context of thought systems or management models, information technology and market forces.

The investigative approach used to support this research has sought to focus on the "product change" or modification process which requires product information to be communicated between supply chain participants—or even shared. The aim has been to develop an improved understanding of the rates of through life design change and generate the knowledge required to enable efficiency improvements from improved information flows and reduced support costs. The following progress has been made:

- Completion of an initial investigation to frame the research;
- Survey analysis of industry challenges;
- Discussion with industry specialists that considered industry challenges by setting them in the context if rates of through life product change;
- Development of a mathematical model to validate observations of industry specialists;
- Development of ten requirements or "principles" to articulate features of a new approach that might help to support improvement.

4 Future State

4.1 Vision

Rapid changes enabled by innovative information technology are driving a revolution in the way industries operate and markets behave. While the markets for complex products, such as aircraft, trains and industrial plant will remain, the way they operate and transact will inevitably be transformed. Competitive forces will require organisations to make substantial adaptations. As the result of a growing recognition of the vulnerability of our planet, the need for greater competitiveness must be considered from a more circumspect perspective that places a pure focus on industrial performance in the context of environmental and social needs. Product information is already a critical resource and this will not change. In future, the ability of engineers, executives, business managers and accountants to work effectively across in the domains of product design, manufacturing, operation and maintenance will be defined by the speed with which they will be able to access and make decisions. One might argue that this is already the case but in the future the reliance on information technology to intuitively collect data and present accurate information (knowledge) in a meaningful way will be complete.

There is much discussion of headline topics such as “cloud computing”, “Big Data”, the Internet of Things and social networking, but the attainment of real progress in the field of managing complex products will rest on establishing ways to manage information and knowledge so that it can be more rapidly deployed to those who need it. Information systems will need to be seamlessly integrated so that they are able to closely support business processes in a responsive way that can adapt to business demands and innovation in product designs. The US Smart Manufacturing Leadership Coalition [19] a US Department of Energy initiative, set-out to establish a roadmap to identify the priorities for modernizing 20th century factories, with 21st century technology and working practices. A prominent feature of this work was the need for a standard industry data model. Further evidence of the need for progress in the development of enhanced information management strategies which this research is investigating is provided by a report from the US Department of Trade which identified that as tariff barriers to trade have fallen, the need to remove standards-related obstacles to the flow of products and product related information has emerged as a key concern. This is an area of particular importance for complex and increasingly global supply chains [20]. However, making progress in this area will require close collaboration between product manufacturers, operators, maintainers and information technology software (ERP and PLM) suppliers.

4.2 Future Product Management

Through life product management particularly in the context of change, is a complicated process that requires the coordination of many activities spanning design, manufacture, operation, maintenance support and disposal. These activities constitute a set of logical processes that reflect the nature of the product management operation. They are highly dependent on accurate information and can have a significant impact on an organisation’s cost base. It is clear that there is a need to promote discussion of the issues that need to be addressed to gain closer alignment between through life design management processes, information technology and the management models used to guide decision making. The authors have previously proposed "Ten Principles" to promote this discussion [21].

The pattern of current activity attempting to make progress is fragmented. There are too many stakeholders seeking to address industry issues in isolation. Furthermore, where leaders have the ability to drive progress, extended lines of communication with other collaborators dilute the impact of initiatives. A fresh attempt is required in which key industry players that have significant market gravitas, collaborate with the major software application vendors to generate the critical mass required for action.

4.3 Future Information Architectures

The industry survey undertaken by this research identified that inaccurate product information was the greatest concern, followed by the management of the product change process, the flow of information between systems and searching for information [22]. These issues are clearly related. If information systems were more closely integrated, the product change process would be better supported, product information flow would be improved and accuracy increased. The closer integration of systems to develop a "system of systems" would also enable easier search. This requires an information architecture that utilises some kind of standard industry data model or common information structure (taxonomy/ontology). Such an architecture would allow the closer integration of information systems and enable information and knowledge to be more rapidly deployed to those who need it. The achievement of this objective will be a critical milestone in achieving the closer alignment between information technology, through life product design management processes and the management models used to guide decision making. Figure 2 illustrates in concept an information architecture that utilises a common information model.

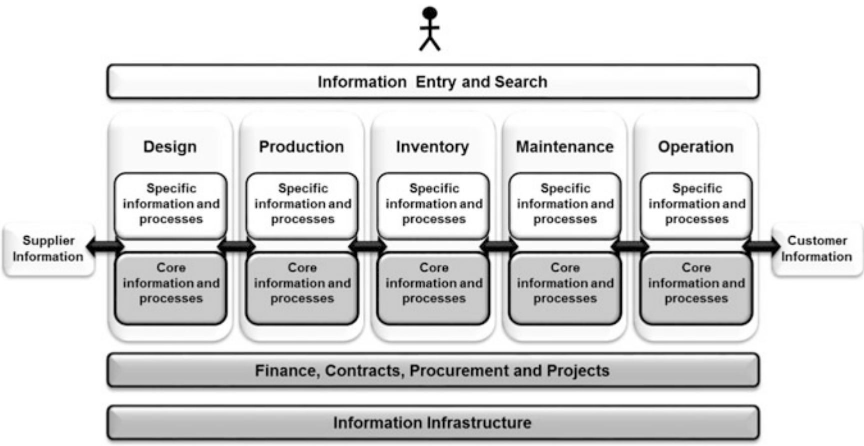

Fig. 2 Future information architecture that utilises a common information model

To make progress there is a need to develop an improved understanding of the barriers to progress. This includes the assessment of the impact made by the effect of inaccurate information and the benefits of improvement. To facilitate such developments industries must consider the role of information in their business model. Research is required to better understand how organisations might offer through life product management in collaboration with other organisations using a shared or pooled information environment.

5 Conclusion

Design change generates significant volumes of information and so product management is becomingly increasingly information intensive. It is now more important than ever for information technology to be closely aligned to product through life management processes and the thought models used to guide decision making. This paper has set-out to articulate the challenges to improving through life product management by considering: the role of innovation in driving industry lifecycles; the relationship that management models and organisational learning have to corporate agility; key trends in product management; and, finally the constraints of current information architectures. These factors shaped the research approach taken.

Rapid changes enabled by innovative information technology are driving a revolution in the way industries operate and markets behave. As the result of a growing recognition of the vulnerability of our planet, the need for greater competitiveness must be considered from a more circumspect perspective that places a pure focus on industrial performance in the context of environmental and social needs. While the markets for complex products will remain, the way they operate and transact will inevitably be transformed. The ability of engineers, executives, business managers and accountants to work effectively across the domains of product design, manufacturing, operation and maintenance will be defined by the speed with which they will be able to access and make decisions. Improvements in this area will require a new type of information technology that utilises a common information model. The development of such a technology will be a critical milestone in achieving the closer alignment between through life product design management processes and the management models used to guide decision making. To facilitate further consideration of the issues a Linkedin discussion forum "Product Change Management Research" has been created. Interested parties are invited to join and support the discussions.

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Road-Mapping Towards a Sustainable Lower Energy Foundry

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Abstract Sustainable development is about reaching a balance between economic, social, and environmental goals, as well as people's participation in the planning process in order to gain their input and support. For a foundry, sustainable development means adoption of strategy and actions that contribute to higher yield with a minimum environmental impact. This new approach forces foundries to change their behavior. Management should include new issues and develop innovative methods, practices and technologies striving for solving problem of shortages of resources in particular energy. Hence, its realization requires updating existing production models. The main message of sustainability for foundries is to expand the range of analysis and focusing on processes. Lean thinking offers numerous opportunities for more efficient resources utilization. Here some energy saving methods toward a more efficient and a sustainable foundry are briefly discussed.

Keywords Sustainability · Foundry · Energy · Lean thinking · Yield

1 Introduction

The world population is continuing to expand, consumption of resources is increasing rapidly, and consequential demands for energy, water and materials are rising. This is leading to the scarcity of energy resources in particular fossil fuels which are threatening everything that depends on it. These trends, combined with the now inevitable impact of climate change, ecosystem degradation, and the exhaustion of a wide range of resources, indicate the need for change in our behaviour.

The ability to take steps towards a more sustainable living and society requires far more than knowledge about sustainability; it requires sustainability literacy [1].

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Making improvements in the environmental and sustainability performance is therefore crucial for achieving a more sustainable foundry. In order for employees at all levels to contribute in making these improvements, a sustainability-literate workforce is needed. Sustainability literacy must involve, alongside appropriate values and ethics, the practical knowledge, understanding and skills to drive positive environmental change within foundries [2].

There are several barriers that prevent a company from becoming energy efficient [3]. The main barriers identified are technical risks, such as the risk/cost/hassle/inconvenience of production disruptions, inappropriate technology for the operation, lack of time and priorities, lack of access to capital and slim organisation. In particular, for SME foundries, the lack of time, skilled personnel and insufficient resources are the largest barriers to energy efficiency. Foundries are the most energy intensive manufacturing sectors with the melting process accounting for over half (55 %) of its energy consumption. The seemingly simple melting operation, such as heating metals to turn them into liquids for pouring, is actually complex; involving a series of steps that incur material and energy losses. These losses are attributable to several factors: Conduction, Radiation, Convection, Stack loss (flue gasses) and Metal loss.

Foundries vary from each other in several respects, such as the metals being melted, alloying requirements, product specifications, furnace capacities and the casting process. There is little potential for a single technology to provide a one size fits all solution. Therefore to achieve maximum possible energy reduction at a given foundry, a combination of energy efficient solutions that are best suited, must be implemented for that individual facility. Studies show by controlling the heat loss by melting operation and control of other process steps, foundries can save about 20–40 % of their total energy consumptions [4]. Jolly argues that the best way to save energy is to minimise material loss and not waste energy to melt it in the first place and increase the yield [5]. This is in accord with designing for zero waste by environmentalists [6]. Salonitis suggests foundries can save materials and energy by lean thinking [7]. Lean thinking methodology is to do more with less human efforts, equipment, time and space while meeting customers with exactly what they required [8]. On the other hand implementation of Six Sigma methodology in manufacturing by collecting data on variations in outputs associated with each process step can help to improve performance and reduce the variations [9]. The purpose of this research is to communicate and explore energy and material challenges and opportunities to identify potential energy savings in foundries. Lean philosophy is introduced to eliminate waste, improve quality and eventually, achieve the goal of energy savings.

2 Low Energy Foundry

There is no such a thing as a low energy foundry. Foundries are high energy consuming establishments within the manufacturing sector. Melting operations require high amounts of energy with efficiencies between 7 and 76 % depending on the capacity, type of fuel, alloy and the melting furnace (Table 1, [10]).

Table 1 Furnace energy efficiency and percentage of metal loss for aluminum casting [10]

Type of furnace	Capacity/kg	Material	Metal loss %	Efficiency %
Crucible (G)	10–1500	Al	4–6	7–19
Induction	1–50000	Al	0.75–1.25	59–76
Reverberatory (E)	500–125000	Al	1–2	59–76
Reverberatory (G)	500–125000	Al	3–5	30–45
Stack melter (G)	1000–10000	Al	1–2	40–45

By adopting concepts such as value stream mapping (VSM), the entire operation of the casting process can be investigated and energy savings can be achieved [7, 11]. Energy mapping can be accounted as a tool to help, visually see the energy flow in the foundries. It can be used to diagnose where energy is strong, and also learn what is effectively improving energy or reducing energy. Energy mapping can be easily deployed in any step of the process to understand and identify the process steps and the hidden energy loss in the foundry. The knowledge obtained from energy mapping helps create learning that is shared with others in the foundry. It is through the process of energy mapping that quantities and qualities of unused energy (typically "waste heat") within the area are identified.

3 Energy Consumptions Pattern in Cast Iron Sand Casting Foundries

Figure 1 shows energy consumption per ton of casting shipped for four cast iron sand casting foundries in three different countries [12, 13]. Similar percentage use of energy between 60 and 70 % relates to melting and holding operations and 30–40 % of energy consumption relates to other process steps such as molding and core making (7–20 %), machining (7–14 %), heat treatment 3 %, air compression (5–14 %) and lighting (1–2 %).

Fig. 1 Percentage of energy consumption of four sand casting foundry in three different countries

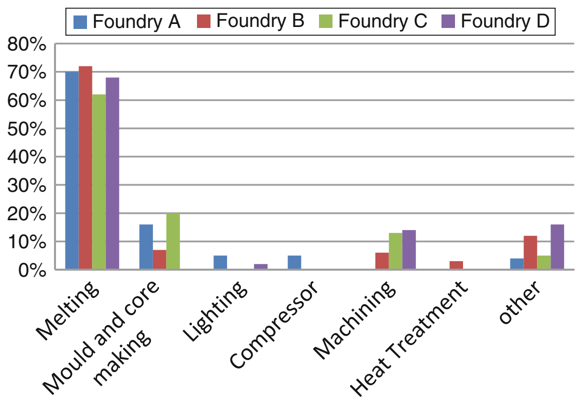
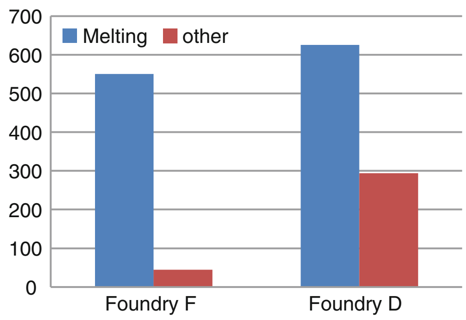


Fig. 2 Energy consumption of two cast iron sand casting foundries



Salonitis proposed an energy audit strategy for identifying the energy consumption of the various components of a manufacturing process [14]. The energy consumption pattern is a useful guide for the energy audit process. The energy pattern shown in Fig. 1, is helpful in understanding the way energy is used in a foundry and helps to follow energy path by identifying areas where improvement may be possible. It is observed, in all foundries, melting is the major section of the casting process. Figure 2 shows energy consumption of two foundries one in the UK and a modern one in Sweden. Foundry D in the UK shows higher energy consumption of around 75 kWh when melting as compared with newly constructed European foundry (F) with high efficient induction furnaces of 6 tons capacity. Other 225 kWh/ton extra energy consumption is related to the process steps such as machining, heat treatment, compressors etc.

3.1 Energy Audit in Foundry F

The energy audit at the cast iron foundry (F) resulted in a number of potential energy efficiency measures which helped to reduce energy consumptions. Installing high efficient energy induction furnaces saved huge amount of energy for foundry (F). Furthermore, large amount of energy savings was found in casting directly into the mold, compressed air system through elimination of leaks, lower idling energy demand during the weekend and holidays, new sand preparation and molding process and more efficient ladle heating, glass roof and walls as well as LED lighting and heating the workshop simply by placing cast parts to cool inside rather than outside. These saved around 300 kWh/ton as compared with foundry (D) in the UK as shown in Fig. 3.

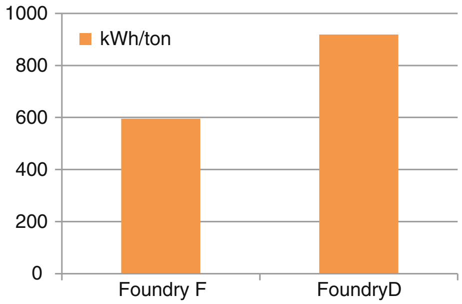


Fig. 3 Total energy consumption of two cast iron sand casting foundries

3.2 Energy Audit in Foundry D

As shown in Fig. 1 most cast iron sand casting foundries follow similar pattern as foundry D. These foundries are using induction furnaces with melting around 625 kWh per ton. Average 75 kWh more than foundry (F) Fig. 2. This difference could be due to age of furnaces, melting temperature (superheat), melt holding time and furnace wall thickness, type of refractory used for insulation, gating and alloy type. Looking at Fig. 3, another 225 kWh per ton of extra energy consumption of foundry (D) is used in other areas such as, molding, core making, fettling, machining, heat treatment, compressors, inspection and utilities with total amount of 32 %. These are areas of interest as there is lack of information about the energy consumption of mold and core making, machining, heat treatment, air compression and utilities.

4 Energy Savings in Foundries

Energy in foundries can be saved, directly through lower fuel consumption and indirectly through lower material consumption. Therefore, for energy savings in the foundry; less fuel and less material should be used for producing a certain quantity of sound products [7]. To accomplish this, an understanding of the flows of energy and materials in the casting process is required. Foundry operation can be divided into sub-processes: moulding, core making, melting, refining, holding, pouring, fettling, machining, heat treatment and inspection. The melting, refining and holding activities consume most of the energy involved in casting (60–70 %); moulding, core making, fettling, machining, heat treatment and inspection consumes (30–40 %) of the energy thus, the direct energy savings should be achieved in these steps. Fettling, machining, and scrap also contain at least 70 % metal by weight of the total melting; therefore, the indirect savings should come from these processes by increase, yield [5].

4.1 Direct Energy Savings in Foundries

The first step for energy saving in foundry is to install high efficient furnace. Otherwise improve efficiency of the existing furnaces. Induction furnace equipment should be with minimum distance to reduce wiring losses. To reduce wiring losses, it is essential to shorten the distance between furnace body and power supply as very large current flows between them. Induction current concentrates in the surface of material to be melted. At higher frequency the current at the surface increases, resulting in better heating efficiency. As molten metal is excited by current opposite to current flowing in induction coil, molten metal is agitated to raise its surface in the center. Agitation makes it possible to ensure uniform temperature of molten metal and its uniform quality [13]. Energy efficient use of medium frequency induction furnaces with constant optimized power charging is reported to be the most economical procedure to operate modern medium frequency melting furnaces. This way the finally prepared melt is tapped completely and the furnace is started up again with solid melting stock [15]. By continuous monitoring and control of melting process, avoidance of lid off periods of furnaces, maintenance of furnace cover and seal cover gaps, investments for heat recovery systems of furnaces and furnace accessories, significant amount of energy can be conserved. The furnace insulation defects increases energy use in intermittent operations. The furnace lining should have high durability, low density, low conductivity and low mass. This is why fire bricks have been changed over to ceramic fibre materials which have high thermal shock resistance. Apart from saving of heat energy, it helps to control molten temperature more accurately [16].

Another important step of the melting process is the preheating of the metal. There are several advantages related to preheating: it can remove moisture and other organics, which helps preventing explosion in the furnace; it can increase the melting capacity of the furnace; and it can reduce the energy required for melting. For cast iron preheating at 600 °C, reduces the power consumption by about 25.4 %, from 626 to 467 kWh/ton and the total unit consumption of energy including gas consumption is saved by 6.3 %. Melting capacity can be improved by 27 % from 0.81 to 1.03 ton/h. It is important to note, oxidation of cast iron and carbon steels are very little under preheating temperature of 600 °C [17].

Heat efficiency can be improved by reducing tapping temperature as low as possible. Heat capacity of molten metal increases with increasing the tapping temperature, and furnace heat loss is fully proportional to melting temperature. (Heat capacity of grey cast iron increases about 20 kWh/ton as its temperature rises per 100 °C).

Energy for melting can be reduced by improving yield by proper design of gating systems which allow the foundry to lower the pouring temperature without affecting the quality of castings. Energy for ventilation also can be reduced by optimising shielding around moulding lines and furnaces and by supplying fresh air correctly. Implementation of modern gating systems will improve yield in foundries so that at minimum a 5 % saving in power consumption is possible. Training for the furnace operators is also essential. It has been shown that operator performance can influence energy usage by as much as 10 %.

The preparation of molds and cores involves significant quantities of sand. Figure 1 shows 7–20 % of energy consumed in foundries relates to this step of production. In a green sand foundry, the addition of water and clay, followed by mechanical ramming are the only remaining steps to making a mold. A foundry that uses chemically bonded sand uses less energy in ramming but this saving is made at the expense of increased pollution from chemical binders. When greater mold rigidity is required, binders stronger than clay are added to the sand. The categories of binders include furan binders, phenolic urethane binders and phenolic ester binders [18]. Recently a new molding process, which consists of low air pressure aeration sand filling and squeeze, has been developed. This new molding can provide several advantages such as, good sand filling, high strength and uniform density mold as well as saving energy in mold making [19]. Energy savings up to 30 % can be realized in a compressed air system by regular simple maintenance measures [20].

4.2 Indirect Energy Savings in Foundries

Improvement of product yield has an important relation to the energy consumption rate of product rather than the power consumption rate for melting. It is important to reduce the weight of metal to be melted by lessening material used. Operational material efficiency (OME) is the ratio between the good casting shipped to customer and the total metal melted [7]. Improving the true yield is probably the simplest way in which foundries can save energy, because this method focuses on increasing good casting production and reducing the total metal melted. It deals mainly with the production process itself, seeking opportunities to save material. It has less relation with the performance of the production equipment. To be able to understand the true yield of the casting process, the entire casting operation needs to be analysed. Using a traditional sand casting as an example, the casting process is analysed briefly in the following paragraph.

Aluminum is a highly reactive material. In particular, when it is liquefied at high temperature, it can react with air, moisture, the furnace lining and other metals. The metal loss during the melting process is due mainly to this characteristic. As discussed before, a casting process can be divided into several sub-processes: six of which, melting, holding, refining, pouring, fettling and machining have a direct relation with metal loss, Table 2.

Table 2 General metal loss during each operation, Data based on general/automotive sand casting production [7]

	Melting	Holding	Refining	Fettling	Machining	Inspection
Metal loss	2 %	2 %	5 %	50 %	25 %	20 %

Figure 4 presents the metal flow during conventional sand casting process. By assuming 1 kg of metal is melted, then after the different stages of the operation, the final casting dispatched to customer only weighs about 0.27 kg. Therefore, the operational material efficiency of this casting process is about 27 %. For conventional casting, 1 kg of good casting requires 3.7 kg of raw materials. Therefore, if the true yield of the casting can be improved, less metal will be required to produce the casting and the energy consumption for the melting could be reduced.

Opportunities to improve the true yield require that the metal loss during each operation must be reduced. Starting with the melting operation, 2 % of the metal loss is mainly due to the oxidation of the aluminum at the surface of the melt. Thus, keeping the melt away from contact with air can reduce the level of oxidation. Normally, this can be done by keeping the lid of the furnace shut and reducing the metal charge time. Secondly, the holding process also contributes 2 % of the loss, which can also be attributed to oxidation (long term exposure). Therefore, reducing the holding time can reduce the metal loss. Thirdly, the refining/cleaning operation contributes 5 % of the metal loss. The loss at this stage of the operation is due mainly to oxidation, hydrogen degassing and impurities. The rate of the loss depends on the cleanliness of the raw material. Thus, good quality raw material is essential.

After pouring, solidification and shakeout, the casting system is sent to the fettling operation. Fettling is used to separate the casting and its running system. Generally, the casting itself is only about 50 % by weight of the entire casting system. Therefore at least half of the metal is chopped off and scrapped. This is the principal cause of metal loss during the casting process. For foundries producing aerospace castings, the metal loss during fettling can be as high as 90 % owing to the strict quality regulations [5]. Thus, reducing the weight of the running system can reduce the metal loss in fettling.

The fifth cause of losses relates to machining. This process transforms the casting into its final shape. It involves grinding, drilling, boring, turning, polishing and any other necessary operations. The metal loss during this stage of the operation is mainly in the form of fine scrap. If the casting can be produced closer to net shape, then the need for machining operations can be reduced. The final type of loss is that of castings that fail the inspection process. Defects such as a poor tolerance, poor surface finish, inclusions and porosity lead to rejection during the inspection. To reduce the level of rejections, the processes of melting, alloying and refining and the design of the running system are very important. The losses in first three steps are permanent losses, which cannot be easily recovered or reused. They can only be

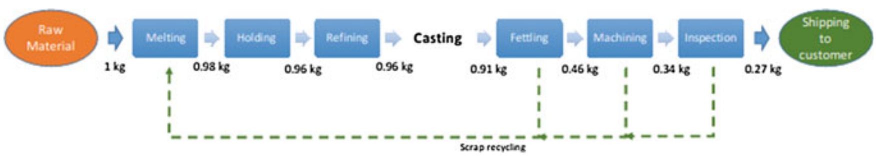


Fig. 4 Metal flow in the foundry [7]

reduced by the methods mentioned. The last three types of loss are assigned as internal scrap. Energy has been used to make and melt this metal and because these losses can contribute up to 90 % of the metal loss in the casting process, energy savings must be achieved by reducing such losses during the casting process.

5 Conclusions

The walk through energy audit and data collections of two sand casting foundries and collected data from literature showed that major consumption of electrical energy in cast iron sand casting processes is due to melting in all foundries. This can be controlled using high efficient furnaces and lean operation during casting. Study shows that the large difference in energy consumption in these foundries is related to the other process steps such as mold and core making, fettling, machining, heat treatment, air compression, inspection and utilities. This can be reduced by appropriate design of mould, gating and sprues, to improve product yield. It is important to reduce the weight of metal to be melted by lessening material used for melting and reducing defective castings as well as decreasing the amount of remaining melt in ladle and furnace. Elimination of leaks from compressed air system, lower idling energy demand during the weekend and holidays, more efficient ladle heating, use of glass roofs and walls as well as LED lighting also can help to save energy in foundries.

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Increasing Production Efficiency Through Electronic Batch Record Systems: A Case Study

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Abstract As manufacturing operations become increasingly sustainable and seek to evolve towards paradigms such as Industry 4.0 and the Smart Factory, the importance of process control becomes paramount. Strictly controlling manufacturing processes improves production efficiency and this can be supported by Electronic Batch Record Systems (EBRS). This study examines this concept in terms of existing literature, and through a case study that explored the implementation of an EBRS at a Life Science manufacturing company, focusing on practical implications of EBRS adoption. The main advantage identified was a 75 % decrease in human errors in batch records, compared to a hardcopy system, thereby yielding improvements in production efficiency. The main disadvantages were cost, implementation resources and the in-built obsolescence of manufacturing software systems. Despite these disadvantages, the company found that implementation of EBRS resulted in a significant increase in production efficiency.

Keywords Sustainable · Manufacturing · Production efficiency · Electronic batch record system · Manufacturing execution system

1 Introduction

For manufacturing to become increasingly sustainable, levels of waste need to be minimized. Sources of waste (for example batches of product rejected prior to release for sale or products returned by customers) can be reduced by increasing the level of control of manufacturing processes. Strictly controlling manufacturing processes is already established as improving production efficiency in a number of

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areas including increasing inter-batch reproducibility, reducing levels of rejected product, decreasing time spent on investigations, and lowering inventory levels [1].

In highly regulated manufacturing sectors such as the Life Sciences every time a batch of a product (such as a pharmaceutical or medical device) is produced it cannot be released for sale until a comprehensive production batch record is fully completed and approved. Historically, these have been hardcopy batch records (HBR) printed on paper, but such systems are associated with disadvantages including generating a high level of human errors and allowing operators to circumvent change control procedures [2]. These disadvantages can significantly increase waste or product requiring to be reworked leading to reduced production efficiency. Software vendors present Electronic Batch Record Systems (EBRSs) as solving many of the problems associated with Hardcopy Batch Record Systems (HBRS) [3, 4] but there has been a paucity of research investigating whether this is indeed the case in practice, and so this paper contributes to this gap in the research. The aim of this study was to investigate the implementation of EBRS at a Life Science manufacturing company, which had previously used HBRS and in particular to answer two research questions:

1. What are the advantages and disadvantages of implementing EBRS?
2. Does implementing EBRS significantly increase production efficiency?

2 Research Methods

The research for this study was undertaken in 2 parts:

(i) A Literature Review to identify any existing published research into the use of EBRS in manufacturing companies.
(ii) A Case Study of the implementation of EBRS in a Life Science manufacturing company.

To understand the impact of EBRS on production efficiency, a case-based approach was employed. Case research is particularly suitable for research of this type, where the focus is on contemporary events and researchers aim to ask 'how' or 'why' questions [5]. Case studies are appropriate for discovery and early theory development in research [6], and allow the researcher to access the phenomena and through the application of a number of tools, develop a rich understanding about it. Semi-structured interviews were selected as the main tool for the case study as the researchers wished to capture the interviewees' opinions whilst avoiding any of the interviewer's preconceptions regarding the subject [5]. Interviews are often preferred by managerial respondents [8] and in this work semi-structured interviews were employed to enable respondents to explain ideas and concepts in their own terms [9] and promote probing by the researcher [10]. The interviews included questions about the planning, length, complexity and relative cost of implementation as well as long term benefits and any disadvantages. However, interviewees were encouraged to talk about their experience of the system in general to avoid the interviewer "leading" the responses. Three interviews were conducted with a Life Science company and these were transcribed and analysed using descriptive codes [11]. The coded data was then sorted into clusters from which, themes, patterns and areas for discussion emerged. As this is a very early exploratory study we use a single case study to inform our work, but as this has implications for external validity we are cautious in the extent to which we generalize our findings. As our intention is to highlight current practice, and develop an agenda for further research this approach is appropriate, however as discussed in the conclusion more detailed research is needed in the further development of this study.

3 Hardcopy and Electronic Manufacturing Batch Records

Modern manufacturing plants need to optimise production efficiency in order to maintain competitiveness [12]. This is particularly challenging in highly regulated sectors such as Life Science where products have to conform to the exacting standards of such quality systems as Good Manufacturing Practice (GMP) and ISO 13485 [13, 14]. The use of HBRS for batch manufacture of products is still common in industry despite the availability of EBRS. In contrast, software vendors promote the replacement of HBRSs with EBRS claiming that the latter can deliver major improvements in production efficiency [3, 4]. Table 1 compares features of the two systems.

From Table 1, HBRSs tend to be associated with a low implementation cost whilst the cost of EBRS is assumed to be high [15]. However, it does not appear that any specific research has been carried out to confirm the complete cost of implementing either system. In the opinion of Adler [15] one of the reasons for higher costs associated with EBRS implementation is that business processes may have to be re-engineered in order to use the system. This is in agreement with studies of Enterprise Resource Planning Systems (ERP) where costs, including business process reengineering, were identified as a barrier to implementation [16].

Table 1 Comparison of features of HBRS and EBRS

Feature	HBRS	EBRS	References
Cost of implementation	Low	High	[15]
Time employees spend handling documents	High	Low	[15, 17]
Human errors associated with system	High	Low	[2]
Effect on change control system	Negative	Positive	[2, 17]
Storage	Physical	Server/cloud	[6]
Security	High	Medium	[18]
Record fragility	High	Low	[3]

Source Authors

Although HBRS are relatively low cost to implement they do result in manufacturing staff spending considerable amounts of time handling and managing documents [15, 17]. This includes time spent on activities such as printing, checking, reviewing, storing and retrieving documents. Notably, Adler [15] reported that introduction of a Manufacturing Execution System (MES) including an EBRS at a pharmaceutical manufacturing facility reduced the time production personnel spent handling documents by between 10 and 30 %. Vaczek [2] reports that HBRS generate high levels of human errors, but our review found no published research studies which provide evidence to substantiate this. The high level of human errors associated with HBRS is a source of low production efficiency in highly regulated manufacturing sectors. This is because quality systems (such as FDA, GMP and ISO) require investigations to be carried out into batches of product where mistakes and deviations from validated processes have occurred. This can result in operations having to spend significant amounts of time on such investigations rather than concentrating on the core task of manufacturing [15]. Deviations during manufacturing processes have to be approved by change control systems. However, with HBRS, operators may judge a change too minor to warrant approval and proceed, thereby creating an event to be investigated and having a negative effect on the change control system. EBRS identifies any deviation however minor and reports it to the relevant manager [17]. The result is that all deviations however minor are recorded in change control.

An EBRS does not require a physical storage area to be set up and maintained (as needed for HBRS) but needs server or cloud based storage. One of the advantages of EBRS is that archived records are immediately accessible by auditors or managers. This is in contrast to HBRS where archived product production records may be held off-site and managers have to wait for several days to gain access. Nevertheless, HBRS could be judged to provide a more secure storage option as access to records can easily be restricted. With EBRS held on servers or cloud companies need to ensure their records cannot be "hacked" or accessed by unauthorised individuals [18]. However, the fragility the documents used in HBRS is far higher than those in EBRS as paper records can easily be mislaid, damaged or destroyed.

Since the 1990's manufacturers of products such as semi-conductors, pharmaceuticals, and medical devices have been utilising EBRS as part of MES to integrate planning and control systems, thereby optimising production efficiency [19]. Saenz de Ugarte et al. [20] define such systems as follows "MES deliver information that enables the optimisation of production activities from order launch to finished goods. Using current and accurate data, an MES guides initiates, responds to and reports on plant activities as they occur". Although some comprehensive MESs that incorporate EBRS are available (Table 2) the reality for many manufacturing enterprises is that they already possess some legacy MES modules such as Laboratory Information Systems (LIMS) or Equipment Calibration and Maintenance Databases (ECMD) and they want to implement an EBRS to add to it [21]. Table 2 lists some examples of commercially available EBRSs and some comprehensive MESs. In the near future, it is envisaged that the majority of large manufacturing companies will

Table 2 Examples of commercially available MESs and EBRSs

System	Name	Vendor
EBRS	InstantGMP™MD	InstantGMP™
EBRS	MasterControl Electronic Batch Records	MasterControl™
EBRS	Syncade EBR	Emerson Process Management
MES	PAS-X-MES	Werum
MES	PharmaSuite®	Rockwell Automation
MES	SIMATIC®IT-XFP	Siemens

Source Authors

implement comprehensive MESs in order to fully exploit the maximum competitive advantage they offer despite the high costs associated with their implementation.

4 Results

4.1 Case Study of EBRS Implementation at a Life Science Manufacturing Company

The analysis of the qualitative data from the semi-structured interviews identified both advantages and disadvantages that the respondents reported. The advantages are summarised in Table 3.

4.1.1 Advantages of Implementing EBRS

The interviews revealed five areas where the implementation of EBRS had resulted in a favourable impact on production. The first of these was a 75 % reduction in human errors in manufacturing batch records, compared to the use of HBRS. When human errors occur in manufacturing batch records, quality systems require investigations to be carried out to identify the root cause and to prevent the same

Table 3 Advantages of EBRS identified from semi-structured interviews

Advantage	Impact
75 % reduction in human errors	Reduction in investigations and waste
Instant access to archived batch records	Faster investigation and audit times
Improved compliance with change control	Reduction in investigations and waste
Supervisory checks discontinued	Decrease in document handling time
Supervisory checks discontinued	Faster product release times
Increased accuracy in measuring materials	Reduction in inventory levels and waste

error occurring again. Such investigations are commonly known as corrective action/preventative action (CAPAs). Therefore, a 75 % reduction in errors results in a significant reduction in the time operations employees have to spend investigating CAPAs and also less waste from products that have to be rejected due to a manufacturing deviation. The significant reduction in errors compared to HBRS is in agreement with [2] and claims of EBRS vendors [3, 4]. Vendors of EBRS also claim that instant access to archived batch records is an advantage and the results of the interviews also confirmed this as being true in this case. This resulted in a reduction in the time spent on investigations and audits as often the batch under review has to be compared to records from previous batches. This is in agreement with Adler [15] and Blumenthal [17] who report that MES systems including EBRS significantly reduce the time employees spend handling documents. Similarly, EBRS implementation had a positive effect on the company's change control system because it does not allow operators to make unrecorded alterations to procedures which they may judge to be "too minor to record". This finding is in agreement with Blumenthal [17] and Vaczek [2]. Identification of the removal of requirement for supervisory review has also been found to be an advantage by Adler [15] and Chase [22] agreed that reduced inventory levels are an advantage of "paperless" manufacturing. Interestingly, the interviews did not reveal a major change in manufacturing process times specifically, (as claimed by some vendors of EBRS systems), but a combination of the benefits listed in Table 3 delivered a significant increase in overall production efficiency for the company.

4.1.2 Disadvantages of Implementing EBRS

The disadvantages of implementing EBRS revealed by the interviews are summarised in Table 4.

Four out of six of the disadvantages identified were associated with implementing the system. The fact that implementation of EBRS is a major project for the company to carry out was seen as a disadvantage by the respondents. Implementation of new

Table 4 Disadvantages of EBRS identified from semi-structured interviews

Disadvantage	Impact
Implementation is a major project	Requires additional human resources, skills and planning
Expensive purchase, implementation and maintenance	Relatively high costs
Cultural issues can affect the success of implementation	Requires change management and additional training
Equipment and other systems need to be compatible with EBRS	Planning and technical investigations
Post implementation challenges	Planning, change management
In-built obsolescence	Implementation cost versus benefit

software systems is often seen as challenging for manufacturing companies requiring additional human resources, skills and planning. This is in agreement with Lee et al. [23] and Marsh et al. [24] who identified allocating resources as a barrier to implementation of MRP systems in SMEs. In addition, Besson [25] identified that ERP implementation could fail due to a lack of planning by managers. The relatively high cost of purchasing, implementing and maintaining the system was also identified as a disadvantage. This is consistent with Adler [15] discussing MESs including EBRS and also with research into ERP implementation carried out by Schubert and Leimstoll [16].

Respondents also reported some organisational cultural issues during implementation, with more experienced, less computer literate operators resisting use of the new system. Cultural issues associated with EBRS implementation have not been investigated fully in the existing literature and so this area could form part of a future research agenda for the use of EBRSs and MESs. However, the existing literature does identify employees "adjusting" to working with new systems [26] and Pan and Tang [27] included cultural behaviour in a review of misfit issues associated with ERP implementation. Therefore, it appears that any planning for implementation of EBRS should include Change Management and provision of any additional training required. The other disadvantage associated with implementation was the requirement to check that existing systems and equipment were compatible with EBRS. For example, balances used for weighing raw materials would need to be able to "talk" to the workstation in order to enter data in the electronic batch record.

The other two disadvantages were associated with post implementation. As is common with the implementation of new systems, there was a "bedding in" phase where workers required additional support from the implementation team while they adjusted to the new methods of working. The only other disadvantage was that once implemented the software system becomes obsolete relatively quickly, due to advances in vendors' products. This shortens the time span over which the benefits of the new system can be reaped and offset against the implementation and running costs.

Despite the disadvantages identified in the interviews all the respondents felt the implementation of the system had delivered a significant improvement in production efficiency for the company. Obsolescence was the major disadvantage they were concerned about as this will probably require the system to be replaced within 10 years, resulting in an overall lower cost/benefit to the company.

5 Conclusion and Directions for Future Work

The literature revealed that despite EBRS being widely used by practitioners in manufacturing industry, there is little published research on the subject. The case study revealed that as with most commercial industrial software systems there are disadvantages and advantages to the use of EBRS. However, the majority of disadvantages identified in this study were associated with implementation of the system and once in use it delivered a significant increase in production efficiency especially by reducing the level of human errors in production records by 75 % compared to HBRS. Nevertheless, the issue of obsolescence of the software system was seen as a significant disadvantage to the study company. The case study also identified that there is an opportunity to form an agenda for additional research in the area of EBRSs and industrial use of MESs to address the lack of publications. In particular, additional case studies could be carried out to extend this study the results of which might then be evaluated in large-scale case research that examines a wide range of industry sectors.

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A Method for Understanding Sustainable Design Trade-Offs During the Early Design Phase

Addison Wisthoff and Bryony DuPont

Abstract The purpose of this research is to present a new method for integrating sustainable design knowledge into the early design phase of new products and processes. A novel organized search tree is constructed to enable the application of sustainable design knowledge before and during concept generation. To further facilitate its application, this search tree is embedded in an easy-to-use web-based application called the GREEn Quiz (Guidelines and Regulations for Early design for the Environment). As a designer progresses through the quiz, user responses are compiled and weighted, and a final environmental impact report is provided to the user. Two research studies are explored to validate the proposed method. The results of these studies show that the search-tree format and presentation of the collection of design knowledge presented in this work provide design engineers with a valuable and informative resource for facilitating the design of products with reduced environmental impacts.

Keywords Sustainable products · Product development · Early design phase · Design for the environment · Sustainable design theory

1 Introduction

Unprecedented growth in both global population and affluence has led to a substantial and continual increase in the design, manufacturing, and consumption of consumer products. The increase in consumer products has led to the vast amount of materials being sent to landfills—where they become irrecoverable—which has begun to create a push from society to start producing new products with a reduced

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environmental impact [1]. Design and development of consumer products is challenging in that there exist very few design methods that inform designers of the environmental impact of new products; in particular, there is a lack of resources that are applicable in the early (pre-concept generation) design phase. This lack of suitable design methods poses an issue, as 80 % of the environmental impact of a product is determined after only 20 % of the design process is complete [2].

Currently there is a series of robust methods that can assist designers to determine the environmental impact of an existing product, after the design has been fully clarified. This method is called a life-cycle analysis/assessment (LCA). As defined by the ISO 14040 standard, a LCA is a "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" [3]. LCA is a useful method for understanding a product's environmental impact, however, the information required to complete a detailed LCA necessitates that the product being analyzed is completely designed and/or in production. Due to this, LCA is extremely useful when used as a retrospective resource.

Recent work has improved the LCA methodology by bringing the detailed results of LCA to an earlier point in the design process, without sacrificing accuracy [4, 5]. These investigations used an artificial neural network to learn from a test set of completed LCA data to infer the environmental impact of potential design concepts during the concept selection phase. Unlike the proposed work (which is intended to be employed as part of the concept generation process) the work by Sousa et al. facilitates the sustainable design of a product *after* preliminary concept generation has been performed, suggesting improvement to a more established design.

Research into improving integration of Design for Environment (DfE) methods has shown that the earlier DfE is incorporated into the design process, the more of an impact it has on reducing the environmental footprint of a product [2, 6, 7]. Other work has found that the more DfE principles are integrated in the process, the greater the chance that the product would become more sustainable as compared to just using a single tool at one stage in the process [8].

There are multiple DfE methods that can be used in the early design phase that this works seeks to improve upon. These methods include environmentally-based Quality Function Deployment (QFD) [9–12]. The environmentally-based QFD-referred to as Eco-QFD, QDFE, QFD-DfE, and ECQFD-allows the designer to include engineering requirements that are specific to possible environmental impacts the product may contribute. Another method is knowing and applying accepted guidelines and principles that have been found to reduce the impact of a product [7, 13–17]. These lists of guidelines are comprehensive, but may be difficult for sustainable design novices to employ. Point based methods, such as Eco-Indicator and ReCiPe focus on quantifying the environmental impact of a product using a point system that is mapped to specific processes and materials. [18–21]. Other methods include software applications that use CAD models [22, 23]. CAD-based LCA methods take advantage of user-generated CAD models and are able to calculate an impact based on the exact dimensions of a design and user-selected materials and processes. There are some limitations to these methods, as the accuracy of the results are based on the availability of processes and materials within the program's database, and require enough design information to be clarified such that a CAD model can be generated.

The work presented in this paper is intended to provide design engineers with a method suitable for use in the early design phase for designing sustainable products. The resulting method is an easy-to-use, informative design resource that will enable designers to understand the eventual environmental impact of products throughout the early conceptual design phase.

To do this, a novel search tree will be developed that combines sustainable design guidelines, international design regulations and standards, empirical design knowledge, and attributes of product cost and preference. The search tree, created in the form of a series of questions and possible user responses, is preliminarily embedded in a web-based survey; the results of the survey are presented to the user as a final report. The goal of this work is to help inform designers of the environmental impact of design decisions as they are being made, and will contribute to the development of more sustainable products.

The following section discusses the new method and the two studies that were conducted to prove the efficacy of the method. Following the methodology section, results of both studies are presented, and the paper concludes with a discussion and concluding remarks.

2 Methodology

Throughout the design of a product, certain design decisions are made that lock in the environmental impact of a product. Such decisions include material choice, where the product is being manufactured and sold, clarifying the intended use and any consumables (such as electricity or consumed parts), and resulting method(s) of disposal. With a considerable portion of the environmental impact of a product being determined in the early design phase, there is a need for a resource that is accurate, informative, easy to use, and applicable throughout the entire design process. To do this, sustainable design knowledge is collected and organized to provide a foundation for the proposed design resource. In the context of this work, sustainable design knowledge consists of sustainable design guidelines, international design regulations, empirical design knowledge, customer preference, and reference LCA data for existing products.

One goal of the proposed work is to create a method that is widely applicable and easy to use regardless of the previous sustainable design experience of the user. To ensure that the proposed collection of sustainable design knowledge will be easily accessible, this information is rewritten into question form. By converting sustainable design knowledge into relevant questions and presenting them one at a time, this facilitates user understanding and application of the sustainability-related principles. Every question is paired with a set of potential user responses, which are presented as a Likert scale set representing neutrality, agreement, and disagreement with the question. The responses vary in number for each question from two (yes/no) to five, with the wording of each response developed specifically for each question. Along with each question and its corresponding potential responses, there is a "More Information" section that provides the designer with clarification for each question. The clarification provides either examples or alternative phrasing to assist in making responses easier to select for a given question. The use and development of the questions, creation of potential user responses, and the additional information presented with each question are specifically designed to increase user comprehension and ability to apply the knowledge presented.

The questions are arranged in a search tree structure, which will facilitate the application of sustainable design knowledge that is directly relevant to the product at hand. In addition, as series of filtering questions are employed that further remove irrelevant questions, such that the designer's question set is selected specifically for the type of product being designed. These features are key to making this design resource easy to use. An example of one branch of the search tree is seen in Fig. 1. The tree consists of preliminary filtering questions and foundational questions; the filtering questions determine which branches of the foundational questions will be included.

In order to make this easy-to-use design resource accessible, the physical implementation is web-based. The programming language Python is used for the development of the quiz's backend, while Django, a web application framework [24], is used to provide a means of placing the quiz on a server, such that the quiz may be accessed by multiple users from any location with internet access. The design resource embedded in the web-based application is herein referred to as The GREEn Quiz (Guidelines and Regulations for Early design for the Environment).

The quiz starts by asking pre-quiz filtering questions to the designer, which are selected to help filter out unneeded questions, thus allowing the designer to focus only on what is relevant to their design. After the filtering questions are completed, the questions from the accordant truncated search tree are provided in a depth-first manner. An example question can be seen in Fig. 2a.

The organization of the quiz is structured such that similar questions—by theme, such as material selection, energy consumption, and transportation—are grouped

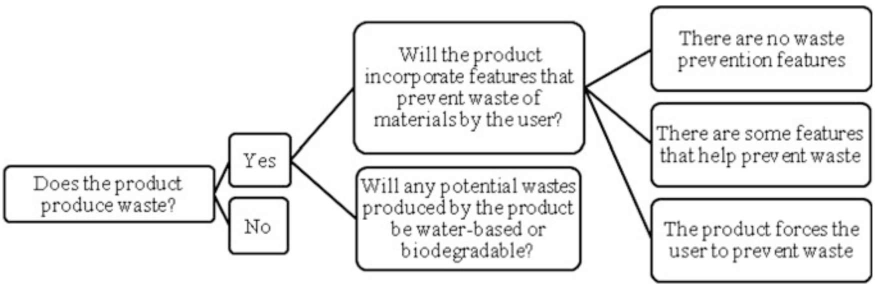

Fig. 1 Example of one branch of the search tree

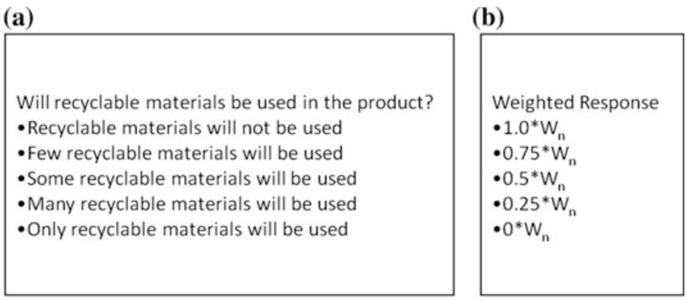

Fig. 2 **a** An example question. **b** Calculating a value for a chosen response

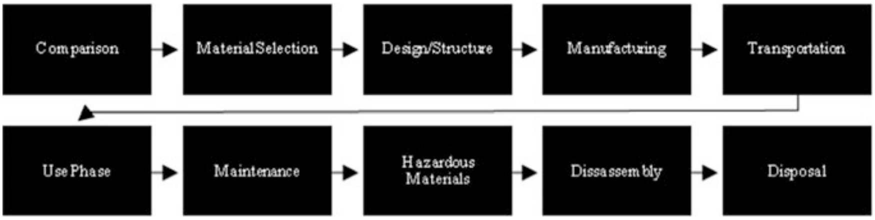

Fig. 3 Flow of categories in the GREEn Quiz

together. These groups follow the flow seen in Fig. 3. The flow starts with questions that compare the current design that is being tested with other competing products. The next two consecutive groups deal with question regarding the design process, such as material selection and structural design. The questions are then grouped into their respective life-cycle phases: manufacturing, transportation, use, hazardous material, disassembly, and disposal. The motivation for this organization is to present questions in an order that better reflects the timeline of the product being developed from its original concept to the disposal of its final form.

Upon completion of the quiz, a report is presented to the designer. The goal of the report is to provide the user of the quiz with relevant information and potential design decisions that will enable the user to improve their design concept by making it more sustainable. To do this, quantitative values corresponding to each user response provide a score for each answered question. An example of the how the responses are calculated is seen in Fig. 2b, where each response inherently has a value correlated to the strength of weakness of that response, multiplied by a weight for each question. This score is then presented in the post quiz report, which displays the summed score of each individual group, as well as a list of the top ten contributing questions that have the greatest impact on the environment. After listing the top ten contributors, a follow-up list is provided to give additional motivation and suggestions to improve the environmental impact of the design. The score received for each question and a paragraph discussing the means and/or motivation on how to improve the score is provided. In keeping with the logical attempt to reduce environmental impact, the scoring is structured in such a way that lower scores are better, enabling the designer to try to reduce both the GREEn Quiz score and the environmental impact of the product concept.

While the version of the quiz presented in this work is exploratory and improvements are already underway, it is pertinent to examine the validity of the current instantiation of the proposed methodology. To do this, we will explore whether this methodology is more useful than the current standard. The current standard—assuming that empirical sustainable design knowledge is not applied—is to employ a list of current sustainable design guidelines found in academic literature. To test this, two validation studies were conducted [25].

The first study was conducted in a junior-level introduction to mechanical design course, where inexperienced students in sustainable design first learn fundamental design principles. Students were divided in to three similarly sized groups, and all three groups were given a sustainable redesign activity to complete. One group (the control group) received only the design activity and no further materials, the second group received a list of sustainable design guidelines from the literature [7], and the final group received access to the GREEn Quiz website. The sustainable re-design activity tasked students with the redesign of a common toaster such that it would have a reduced environmental impact. All students were given 30 min to complete the activity to the best of their ability. After completion of the activity, 82 total students participated with 27 students acting as the control, 26 students employing the guidelines, and 29 students using the GREEn Quiz.

The second study was conducted in a graduate-level mechanical design course that specifically focused on sustainable product design, which can be assumed to have more sustainable design knowledge. The course consists of a term-long project, where students learn how to develop a new sustainable product, from an initial broad scope to a patent-ready product, within groups of six students. The purpose of this study was to explore the efficacy of the GREEn Quiz as applied during concept generation. To accomplish this, the study was broken up into two parts: the first was to familiarize students with the guidelines and how the GREEn Quiz worked, and the second was to compare designs that are generated before and after taking the GREEn Quiz. Students were asked to generate concepts individually during this phase of the project, generating at least ten concepts on their own, in the form of sketches and text callouts. After completing the first design concept unassisted, students were then asked to utilize the GREEn Quiz as applied to this first design concept. Upon completing the quiz, the students were asked to redesign or improve upon their concept such that the product concept would be more sustainable. From this study, a direct comparison can be drawn between preliminary expert sustainable design knowledge and the benefits of using and applying the GREEn Quiz.

3 Results

The first study conducted in the undergraduate class focused on how inexperienced designers in sustainable design would perform while using various sustainable design resources to re-design a product. In Figs. 4 and 5, the average number of design decisions are shown with respect to the three different groups (control, sustainable design guidelines, and GREEn Quiz), with Fig. 4 showing all design decisions, and Fig. 5 showing all stated sustainable design decisions. These design decisions were determined empirically, and are considered to be unique features that are either specifically called out or drawn. Examples of such features include a solar panel embedded in a toaster, as seen in Fig. 6, or a text call-out stating the

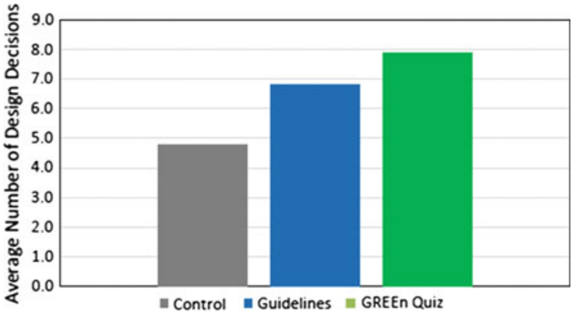

Fig. 4 Average number of design decisions

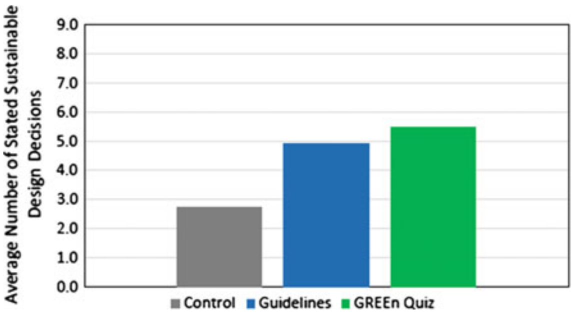

Fig. 5 Average number of stated sustainable design decisions

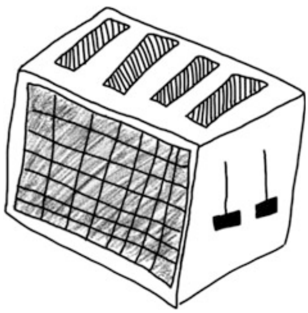

Fig. 6 Example sketch of a sustainable design decision: solar-powered toaster

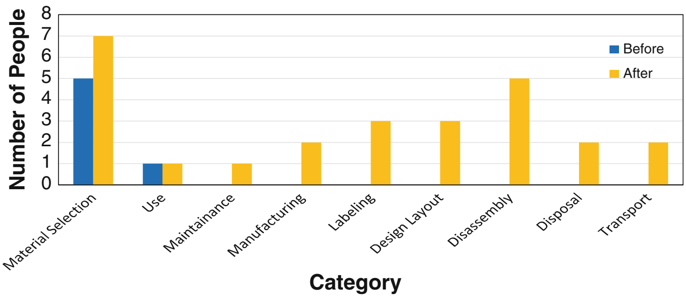

Fig. 7 Referenced sustainable decisions: before and after the GREEn Quiz

material for the housing would be made of recycled steel. A sustainable design decision is classified as a feature or aspect of a sketched design which follows one or more ideas captured in sustainable design knowledge within the quiz.

The second study, conducted in the graduate level class, was focused on designers with previous knowledge in sustainable design. During concept generation, students were instructed to take the GREEn Quiz for a particular product concept. After completion of the GREEn Quiz they were told to redesign their initial concept such that it would be more sustainable. The results of this study are shown in Fig. 7. For both before (blue) and after (orange) employing the GREEn quiz, Fig. 7 shows the number of students who made reference to a question within the GREEn Quiz, by the category in which the referenced question were organized. It is important to note that a given person is only counted once per section even know they may have referenced multiple quiz questions that relate to a single category.

4 Discussion

Two studies were conducted to test the validity of the GREEn Quiz. The first study (the undergraduate study) was to verify that the GREEn Quiz would be useful as a design tool and benefit the designer in generating sustainable product designs. As shown in Fig. 4 these results imply that when students are given a resource (be it the list of guidelines or the GREEn quiz), they are able to call out and/or include more design decisions than the control group, which did not receive any additional material. Moreover, the GREEn Quiz group was able to generate the greatest number of average design decisions for that redesign activity. By having directly-applicable and relevant concepts presented in the quiz, the students were able to implement sustainable design knowledge—of which they were previously unaware—and apply it to their redesign.

In Fig. 5, the average number of sustainable design decisions for each group is shown. As expected, the trend in Fig. 5 is similar as to what is seen in Fig. 4, since the sustainable design decisions are a subset of the total number of design decisions referenced in Fig. 4. The GREEn Quiz is intended to assist the designer in making more sustainable design choices, and these results support the statement that by using the proposed method, a designer can design a product that has more sustainable design considerations.

The second study tasked graduate students to evaluate and redesign concepts that they generated for their team-based product design term project affiliated with the class. This study allows for the ability of making sustainable design improvements to be tested in a before-and-after setting. As seen in Fig. 7, prior to using the GREEn quiz, the students mentioned only a few potential sustainable design decisions, in a narrow breadth. After taking the GREEn Quiz and redesigning their initial concept, there were more students making sustainable design decisions and in a wider breadth of categories. The increase in breadth can be attributed to the wide array of sustainable design knowledge encompassed in the quiz. This result shows that when users of the quiz are exposed to knowledge they might not know in an easy-to-interpret format, they are capable of directly applying it in the development of design concepts with a reduced environmental impact.

5 Conclusion

This paper provides a new method to enable designers to determine which design decisions made during the early design of a product will have the highest environmental impact and to encourage the development of sustainable products. The proposed search tree implemented in the GREEn Quiz will provide designers with an easy-to-use method that can assist them in the conceptual design of such products, by supplying them with development questions, feasible responses, and a corresponding report that indicates where design improvements can be made. Two case studies showed a positive relationship between employing the GREEn Quiz and the ability to make more sustainable design decisions during the early design phase, and the ability for GREEn Quiz expert users to explore a wider breadth of feasible sustainable design decisions than when relying on expert knowledge alone.

Future work includes developing an advanced weighting system such that the results of the GREEn Quiz provide relevant quantifiable information to the designer. By allowing the weights to create more meaningful results, it can provide the designer with the ability to make critical design decisions with confidence, knowing that the changes they are making will make the largest impact of reducing the environmental footprint of that product.

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Achieving Sustainability in SME Manufacturing Operations via the Use of Flexible Integrated Technology and Product Symbiosis

Alan Davies, Michael Packianather, John White and Sajith Soman

Abstract This paper outlines how the economic and environmental sustainability of SMEs in particular can be improved by ensuring that their manufactured product's *Sustainable Life Cycle Costs (SLCC)* are minimised. It advocates that this may be achieved through the correct use of *Manufacturing Management Informatics (MMI)*, initially to ensure the correct selection of engineering materials and subsequently for product-manufacturing system—process—recycling design. By adopting such an approach, which in essence employs *Flexible Integrated Technology (FIT)* it is proposed that a company can not only achieve a significant reduction in their operational costs but also establish a lasting improvement in their productivity, competitive position, economic and environmental sustainability and overall profitability. Within the paper, a proposed methodology for achieving minimum sustainable life cycle costs is outlined. This emphasises the requirement for and correct use of manufacturing management informatics in product, manufacturing system, process and recycling design, to ensure efficient low cost sustainable manufacture. A case study is included, which assesses the effectiveness of the approach proposed by utilising a comparative before and after example in a construction industry SME. This indicates how the proposed methodology can be implemented in an incremental and concurrent manner via the use of existing concepts, strategies, innovative thinking and suitable manufacturing management informatics software.

Keywords Sustainability · Flexible integrated technology · Product symbiosis

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1 Introduction

The recent economic downturn, which followed the banking and consequent financial problems of 2008, has engendered a climate of fierce competition in the global market place for all types of manufactured goods. As governments have attempted to rebalance their economies and engender economic growth in their manufacturing sectors, many companies have been forced to ensure that as far as is possible, the costs associated with their production operations are kept to a minimum without sacrificing product quality or innovation. Traditionally, company operating costs have been identified as belonging to either a fixed or variable expenditure category. Fixed costs are generally of a one time nature and are usually independent of production volume. On the other hand, variable costs can be split into one of a further three categories which are normally linked to output levels, and these are *labour*, *materials* and *overheads*. Therefore for SMEs in particular to remain competitive and profitable in a market place where all too often the product sales price is capped by a need to match, or better the competitions offering, a company must be extremely conscious of the need to hold down costs in each of these areas.

The days of a cost plus philosophy should through stiff competition in the marketplace have disappeared forever in most industrial companies, with the exceptions being perhaps in firms that are involved in various areas of advanced or cutting edge technology, wherein considerable research is required to produce a viable product and much *uncertainty* may reign in its development. Typical examples of such profit risky manufactured items lie in the Defence, Pharmaceutical, Medical and Agro-Chemical sectors of industry. However, even with the above caveat, these product areas are now under attack by commercial customers and taxpayer representatives alike to eliminate the cost plus nature of their development contracts for something more competitive.

2 Background/Literature Review

For many companies including SMEs adopting a policy of reducing the labour force, obtaining alliances with overseas partners or moving manufacturing operations to countries where labour rates are low, have thus far allowed them to remain competitive and profitable in the market place.

In the short term this may have been a strategically correct decision for a company unable or incapable of reducing its costs in any other way. In the longer term however it may prove to be a strategic mistake as orders for a firm without an in-country recycling capability become more difficult to obtain, fuel for transporting goods in both directions overseas becomes more expensive, and insurance plus security rates rise, all of which will force product transportation costs to escalate and lead to an increase in the item sales price. Such factors are worrying for a company's competitive position especially when taken together with a degree of uncertainty in, or the lengthening of product delivery times, and all as a consequence of the distance between suppliers, the manufacturing/recycling facility and the customer [1]. It is important to note that the last two elements have long been recognised as vital competitive features in the market-place together with both the direct and indirect production costs [2]. Hence the emphasis which has been placed in recent years on the design of company supply chains to achieve if possible very high operational flexibility consistent with minimum delivery times and costs [3].

Consequently, we have seen over the last few decades a switching of costs for many companies between the categories of labour and that of overheads, or direct to indirect costs, as a simple way of achieving a substantial cost reduction in the area of manufacturing operations. This *outsourcing* may well turn out to be a strategic error for those companies who have moved their manufacturing facilities overseas, for it relinquishes an important aspect of cost control. That aspect being that items such as fluctuating exchange rates, fuel and other transportation costs are *external* factors over which company managers have little or no control and less influence, as illustrated by the collapse of some low cost airlines [4] and many independent hauliers [5]. Shipping and airline companies in particular have high operational, maintenance and personnel costs to cope with, in addition to fuel and other transportation linked commodity price variations. Thus it should therefore be recognised by manufacturers of consumer products, that operating and maintaining rail, maritime, aviation, road or other transport systems require highly skilled and knowledgeable personnel, with all the attendant labour rate values that this implies.

It should also be noted that such firms are subject, possibly sensitive to, many problems in a global economy not the least of which are wars, migration, strikes, piracy, terrorism, natural disasters and adverse weather conditions all of which may have serious economic consequences such as higher insurance and security costs, a supply chain delay, ransom, or damage to incorrectly packaged products [6]. In addition, another factor which is becoming increasingly relevant to product cost in an inclusive marketplace is that of global warming and environmental or *green* issues generally. So much so that the cost of a product's environmental sustainability or recycling requirement, and its carbon footprint or extent of CO_2 emissions, is now giving rise to high levels of concern worldwide, and is becoming more and more important in respect of achieving a worthwhile sales volume [7].

In a general sense therefore, environmental sustainability can and has been defined as:-

> Meeting the needs of the present generation without compromising the needs of future generations [8].

If we accept this utopian statement at face value, the problem of achieving high operational efficiency in a manufacturing system at minimum cost while satisfying customer's and society's *green* concerns, is therefore not one which can be ignored by companies in the long run or solved necessarily by *outsourcing* or fleeing countries with high labour cost economies. Rather it is a management challenge to be solved by innovative thinking in respect of many issues including plant location, material, component and product design/transportation, plus manufacturing system/process recycling technology and suitable cost control via manufacturing management informatics. It should not be regarded as an insoluble problem or too hard to do! However, it will require stakeholders such as governments, manufacturing companies, investors and consumers to reconsider their strategic/purchasing choices and take a more measured and long term view of their activities and objectives if any form of environmental sustainability in manufacturing is to be approached never mind achieved.

Accordingly, this paper assesses the various factors involved in attempting to achieve a cost sustainable manufacturing situation and how these are affected by developments in manufacturing management informatics for market analysis and order processing, material selection and product design. In addition, it explores how such management informatics may be implemented in a typical SME to design an efficient production system and associated material processing/recycling capability so as to achieve minimum operational cost and environmental impact, whilst contributing to company economic sustainability without if possible sacrificing innovation and product quality. A tall order and neat trick if it can be done?

3 Sustainable Product Design, Material—Process Choice and Utilisation

With international competition in every field of engineering being intensified by the trend towards globalisation and further increased by recessions within the economic cycle, it is becoming obvious that correct material selection for sustainable product design, manufacturing process choice and cost effective resource utilisation is an important topic in engineering management. In the current business climate, the economic design, manufacture and recycling of consumer products through the correct selection of materials and processes is vital to ensure a company's cost competitiveness, maximum profitability and economic/environmental sustainability. For the design engineer, the choice of what material to use in a particular engineering product or component has never been wider. A vast range of materials now exists in which several may offer the properties necessary for the cost effective manufacture of a functionally successful engineering product or component. Under normal circumstances therefore, an initial list of possible materials and associated processes is narrowed down by the designer and manufacturing engineer through use of precise operational property and processing requirements as criteria together with the form of supply, acquisition, waste processing and salvage or recycling costs. However, it must be noted that it has long been recognised that the task of cost effective materials and manufacturing process selection for any component or product should be part of an integrated and numerate manufacturing and design system wherein although many concurrent actions take place, "Nothing is decided by one individual alone without an appropriate review" [9].

This linkage between the design and manufacturing of an engineered product is currently enshrined in the concept of *design for manufacture* and as outlined above, is a team based activity vital to the minimization of cost in production. As the introduction of a new product is always uncertain in terms of profitability, to achieve the maximum chance of success, the choice of materials and processes used is therefore a key strategic decision, one which now must also encompass *design for resource reduction, reuse—recycling or remanufacture, final disposal and environmental impact*. The outcome being in terms of product value for money in service and competitive leverage or differentiation in the market place together with if possible, a low production, disassembly, reengineering and environmental cost. This is in effect *design for sustainability*. As previously noted, in today's world there is a wide range of differing materials and manufacturing processes available for the production of engineered products and as a consequence, a correspondingly extensive range of material properties exists. To be useful therefore, a material must possess a combination of properties or features which may not necessarily be wide ranging but which will suit a given application. Several electronic, web based and hardcopy databases are now available to assist engineers in the selection of materials for a particular usage, which although extensively detailing their physical characteristics and properties, may not necessarily indicate aspects of their overall life cycle assessment and sustainability cost in a suitably useable way [10].

In a generic sense, it is accepted that most designs can be described by the use of some fundamental attributes. These are typically its functionality, performance, appearance, quality, method of production and cost. Although the process of formulating a list of possible materials and manufacturing processes to produce a particular design is usually carried out in terms of the required functional and performance properties, the final choice must involve *cost and revenue generation as the main criterion* to ensure company economic sustainability. Appearance and quality are normally secondary considerations depending on the product and dictated by what is achievable within a target manufacturing cost. This is obvious as the production cost has to be traded off against function/performance and appearance/quality otherwise a penalty maybe incurred in the form of the cost/sales price, with potentially minimal gains in product competitiveness or marketability. Where there is a competitive situation and materials are being used on a cost/unit volume basis, it should be noted that material processing costs in manufacture can become extremely significant, particularly if dimensionally tight tolerances and/or a good surface finish is required.

In addition and as indicated previously, further selection criteria may well become important in the near future, if current *Life Cycle Assessment (LCA)* procedures are developed to the point where they can be used as practical tools within the design process. Any such new criteria will undoubtedly reflect both the sustainability cost and environmental impact involved in the whole of a product's lifecycle and not simply its manufacturing cost. Accordingly, and as the product's *Life Cycle Cost (LCC)* would reflect the expense involved in all aspects of its creation, existence, use, recycling or disposal, this value in the future could possibly supplant manufacturing cost as the prime reason for a particular design selection.

This may well be the case if governments were to for example legislate to recover any costs relating to environmental damage and its subsequent repair from product manufacturers rather than the user/taxpayer. However, any such levy on production volume, reflective of a product's environmental damage, recycling or disposal cost would probably be passed on to customers as at present in the sales price or through some form of purchase tax. So, if the market for that item was competitive, punitive legislation of this type would certainly concentrate the mind of management and design staff in respect of sustainable material—processing selection and utilisation to achieve cost effective product differentiation.

4 Sustainable Product Design, Material—Process Utilisation to Achieve Cost Reduction

In a practical sense, given the limitations and state of knowledge available in respect of the methodologies of complete sustainable life cycle assessment and costing, the results of applying these techniques to potential manufactured products yield at best relative ballpark estimates for competing designs. When faced with this situation, the best a manufacturing company can do at present is to limit any such assessments to the so called *gate to gate option of LCA—LCC* wherein the materials and processes to be used in the proposed product and their associated costs are precisely defined [11]. This allows competing designs, materials and processes to be directly compared with confidence at the design stage and a selection made on the basis of given criteria. There are many techniques available to the engineering production/product design team of a company for use in this area of attempting to minimise waste and maximise the efficiency/effectiveness of manufacturing systems. The most popular currently being those based on the Japanese philosophy of manufacturing and its extension into lean and agile production. Notable examples include Total Quality Management (TQM), Just-In-Time (JIT), Continuous Improvement (Kaizen), Total Productive Maintenance (TPM), 5's, Poka-Yoke, Six Sigma and Product Symbiosis. In addition, it should be noted that other methodologies are also available to address company-wide operational activities such as Business Process Re-engineering (BPR) [12] and these have also gained advocates for their application in this field of industrial management [13].

As originally conceived 'fit manufacturing' advocated the use of lean and agile manufacturing within a company to reduce its costs and thereby achieve economic sustainability [14]. *Lean manufacturing* evolved from the Toyota Production System (TPS) and can be defined as:

> A set of techniques that focus on value addition by the elimination of waste in the production system.

It is a philosophy which was developed from the perspective of the customer, wherein value is defined as any process or action which the customer will pay for. Any other process or action within the manufacturing system is classified as waste and as far as possible eliminated. As it is process driven, a criticism of lean manufacturing on its own is that it lacks the ability to implement a companywide holistic approach to sustainable manufacturing. *Agile manufacturing* on the other hand may be defined as:

> The ability of a company to rapidly adapt to changes in customer requirements and fluctuations of sales in the market place.

Potentially, it can provide a company with competitive advantage through supplying the right product to the market faster than its competitors. If adopting this approach, the firm's administrative and manufacturing processes should be specified in such a way as to respond rapidly to changes in its trading environment, without if possible the need for additional capital investment. While recognising both strategies are applicable within a company seeking to become sustainable, *Sustainable design and manufacturing* can be defined as:

> The ability of a company to innovate across the whole range of its activities, improving its operational efficiency and effectiveness, product range and manufacturing/recycling capability thereby achieving profitability year on year and providing opportunities for company economic and environmental sustainability plus productivity growth.

Whereas waste in the production system can be tackled by the techniques/strategies mentioned above, it should be recognised that product symbiosis allows waste and recycling to be minimised at the design stage, by identifying additional products that can be manufactured from the surplus material left over from the manufacture of the prime product. In traditional manufacture such surplus material is regarded as waste and often ends up in landfill if not easily recycled. Product symbiosis however has the potential to reduce or eliminate such waste depending on the correct application of techniques available in product design and system engineering coupled with the ingenuity of the designer and manufacturing system engineer. Multiple product symbiosis created and implemented at the design stage can thus improve the sustainability of a company in both an economic and environmental sense. Application of the technique in practice is not limited by company size, for in many cases where in-house production of symbiotic products is not desired, then outright sale or disposal of waste to profit sharing spin off companies is possible. Alternatively sub-contractors may be used to manufacture the secondary and tertiary products. By receiving their raw material as a free issue from the lead firm a controlling interest can be maintained by the prime manufacturer if so desired. However, a lack of imagination to investigate, identify, design and produce the additional products from the waste material generated by the prime manufacturing activity, appears at present to be the main stumbling block to implementing product symbiosis in many firms.

The conception; design, manufacture and recycling of sustainable consumer products is a complex process, one which may be outlined conceptually, in an idealised and methodological form, as shown in the flow diagram of Fig. 1. A simple study of this diagram will result in the obvious conclusion that:

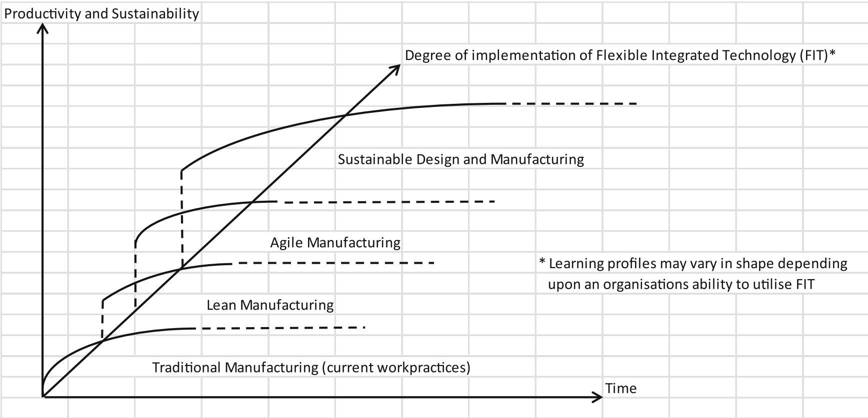

Fig. 1 The anticipated rise in productivity and sustainability with the introduction of flexible integrated technology (FIT)

> The effective collaboration between the product design and manufacturing engineering departments in any company is the key to achieving both economic and environmental sustainability for the firm and its products.

Thus the link between product design, material selection and manufacturing system—process design to achieve minimal cost, waste and energy usage in product operation and production/recycling may clearly be seen to be a key objective in the search for company economic and environmental sustainability [15]. The use of flexible integrated technology linking these company departments can act as both an enabler and a driver of effectiveness in this area of manufacturing management informatics. By integrating product—system—process—recycling design, together with life cycle assessment and cost as well as that of energy use in production and ease of final item disposal a significant advance in manufacturing sustainability can be achieved. It can also provide through the use of suitable metrics an indication of company productivity and operational cost effectiveness via appropriate information system design and software implementation.

5 Application Case Study

The example described below relates to the manufacture of two pre-fabricated modern building products in a small to medium sized enterprise. These are brick clad archway facings for window and door openings together with brick clad pseudo chimneys for domestic dwellings. In this example these two items represent the prime company products. At present all work parts are transferred manually between and within manufacturing system work stations while in future it is envisaged that this will be done using automatic transport systems. The current and

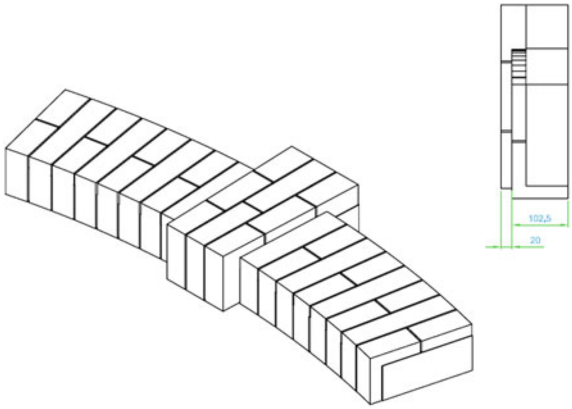

Fig. 2 Representative example of a segmental arch CAD drawing

proposed processes required to manufacture these products and dispose of waste are briefly outlined below and diagrammatically in Fig. 2. At present the company is at the stage of implementing lean manufacturing to its shop floor activities and introducing innovative software to its administrative processes. Both these developments are being undertaken concurrently in order to improve its agility in fulfilling customer orders, together with the introduction of new technology in the form of brick cutting and woodworking machinery.

Archway products current manufacturing process: Archway products are ordered by communicating the appropriate specification to the company by telephone, email or post and then manually scheduled for production. An archway is marked out on a MDF/insulation/MDF sandwich panel using an appropriate template and cut out using a panel and/or band saw as required. Pre-cut 25 mm thick brick slips are also marked out using the appropriate template and the brick material is cut to size using a cutting saw as necessary. The cut brick slips are subsequently adhesively attached to the front panel of archway to complete the product.

Archway products proposed manufacturing process: Archway products are ordered utilising company designed web based Computer Aided Design (CAD) software. Linked production planning and control software dynamically schedules the product for manufacture according to the production programme and required delivery date. The archway design is converted into a Computer Numerical Control (CNC) programme and sent to CNC based cutting machines to manufacture brick slips plus the MDF/insulation/MDF sandwich panel as required. The final product is assembled and adhesively bonded via CNC robotic systems to complete manufacture.

Chimney products current manufacturing process: Chimney design is undertaken using CAD software to interrogate architect's building design drawing thereby generating the desired product specification. Chimney order is then scheduled for production manually. Chimney box frame and plywood panels are marked out manually from printed CAD drawings and cut to size using a panel and/or jig saw as required. Chimney box panels are assembled into a frame and

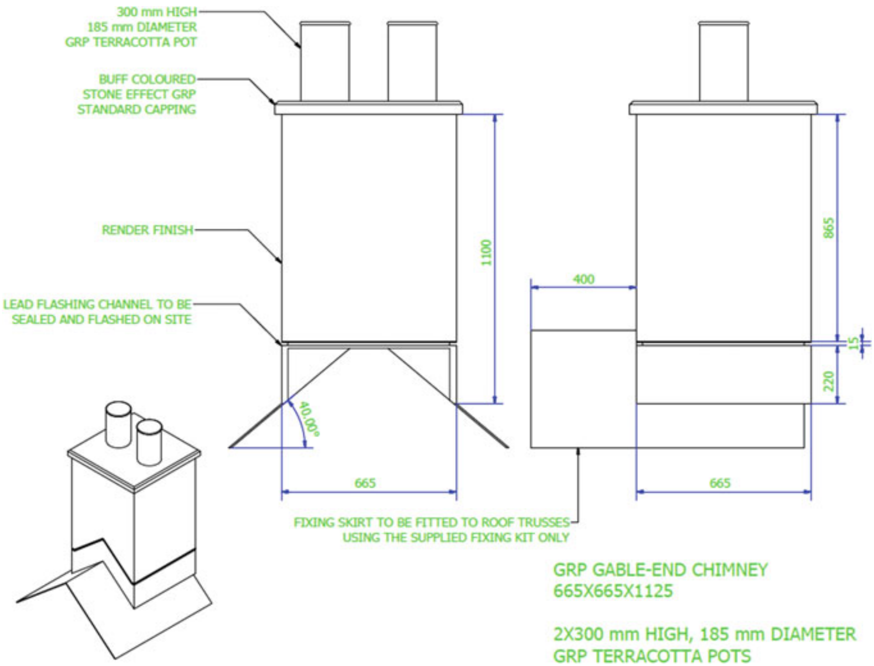

Fig. 3 Representative example of a chimney CAD drawing

corners rounded off using a router as necessary. Weather seal assembled chimney box utilising manual glass fibre spraying system and fit to base plate. Adhesively bond pre-cut 25 mm brick slips to all four faces of the chimney box. Mechanically attach a vacuum moulded plastic chimney cap and pot to chimney box to complete product (Fig. 3).

Chimney products proposed manufacturing process: Chimney product is ordered utilising company designed web based CAD software. Linked production planning and control software dynamically schedules product for manufacture according to production programme and required delivery date. Chimney design is converted into an appropriate set of CNC programmes and sent to CNC based cutting machines to manufacture brick slips, base plate, frame and chimney box panels as required. Assemble chimney box panels to frame and round off corners as required using CNC robotic systems. Weather seal assembled chimney box via robotic glass fibre spray system and fit to base plate. Adhesively bond pre-cut 25 mm brick slips to all four faces of the chimney box via CNC robotic systems. Mechanically attach a vacuum moulded plastic chimney cap and pot robotically to complete product.

The expected benefits which are anticipated to arise from the revised production systems outlined above are considerable, including significant cost savings in both material inventory levels and waste disposal. The existing waste disposal costs for the company is given in Table 1.

Table 1 Waste disposal information [16]

	Type	Cost	Quantity	Frequency
Paid by company	Brick cuts	Collected for free.	Per skip	Once a week
	Brick slurry	*£350*	Per bag	4 bags collected once a month
	General waste (including ply)	*£600*	Per 40 yard skip	2 times a month
Revenue generating	Metal	£265 (£210 for 21 kg of lead and £55 per 46 kg of steel)	Per skip	Quarterly

Further benefits in the form of increased production capacity, productivity and the development of additional revenue streams via the introduction of new products, is also anticipated. In addition company turnover is also expected to increase with a reduction in product lead times and an increase in customer orders.

6 Conclusions

Lean manufacturing has been successfully implemented in many companies both in the UK and worldwide. It has without question when correctly implemented reduced the amount of cost and waste generated in the manufacturing process by those companies which have adopted the strategy. More questionable is the impact achieved by the concept of agile manufacturing, which arguably extends the strategy of lean beyond that of simply saving the cost and extent of shop floor waste, into the area of simplifying administrative processes and minimising capital expenditure. The extent of the take up of this agile concept in manufacturing companies appears to be less extensive than that of lean, owing mainly to the management challenge firms face in trying to effect a major cultural change in their organisation. Sustainable design and manufacturing further extends both of the above philosophies to provide in the view of the authors a compatible strategic framework, wherein a company can move in a stepwise and concurrent manner towards achieving economic and environmental sustainability. The combination and use of design and manufacturing techniques such as product symbiosis and flexible integrated technology linked with those in lean and agile production provide as shown in the example, a powerful means by which companies can become truly sustainable. However, the main stumbling block remains for most manufacturing companies, one of the desire to become sustainable and of getting managers to accept the challenge of implementing the appropriate production strategies via Flexible Integrated Technology, through which the necessary cultural change in their organisations may then be effected.

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Part IV
General Track 4: Decision Support and Sustainability

Business Model Experimentation for Sustainability

Nancy M.P. Bocken, Ilka Weissbrod and Mike Tennant

Abstract Business experimentation is a key avenue for accelerating change for sustainability. In contrast to experimentation in natural sciences, benefitting from controlled situations, business experimentation aims to explore the diverse possibilities that a business could create value from, or understand what works in which particular situations in a real life business context. While at present most popular with start-ups, this paper argues that large businesses can also find inspiration in business experimentation to develop sustainable business models and accelerate positive change for sustainability. Five illustrative cases are included of business experimentation for sustainability by focusing on pivots (modifications) in the business model. This paper only scratches the surface of the potential impactful new research field of business (model) experimentation for sustainability. Future work on sustainable business experimentation for start-ups and mature businesses is viewed as a powerful future research avenue to accelerate change in industries.

Keywords Business experimentation · Lean start up · Corporate sustainability · Radical innovation · Disruptive innovation · Sustainable entrepreneurship

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1 Introduction

The evidence on climate change coupled with a growing world population makes it clear that our current economy cannot be sustained [1]. A growing global population and pressure on resources are creating increasing sustainability challenges for industry and society and business as usual is not an option for a sustainable future: a fundamental shift in the purpose of business and almost every aspect of how it is conducted is needed [2]. Business experimentation is viewed as an important lever to change the way business is done [3, 4]. The business model for sustainability sometimes referred to as 'sustainable business model' in short, is increasingly viewed as an important 'lens' for systems-level innovation [5–7]. Hence, this research investigates sustainable business model experimentation as an important driver for sustainability.

This research addresses the following questions: What could business model experimentation for sustainability look like? How can it help drive positive change for society and the environment? These questions are investigated by a range of illustrative case studies.

2 Literature

This section reviews the literature on sustainable business model innovation and business experimentation.

2.1 Sustainable Business Model Innovation

Business models conceptually describe the way business is done [8]. They serve as a holistic framework, connecting different actors such as the focal firm, suppliers and other partners that create value to customers as the recipients of value. Typically, business models are described as comprising a value proposition (product/service offering), value creation and delivery (the way value is provided), and value capture (how money and other forms of value are captured) [2, 9].

Innovation in the business model itself offers the potential to integrate sustainability considerations far more fully into the purpose of the firm [9]. Sustainable business model innovation 'is concerned with innovation in the way business is done by generating competitive advantage through superior customer value while contributing positively to the company, the environment and society and minimising harm' [10, 11].

The areas of green (e.g. [12]), social [13] and closed loop [14] business models have individually gained a lot of traction. The sustainable business model archetypes (Fig. 1) were developed to create a unifying platform of possible sustainable business model innovations.

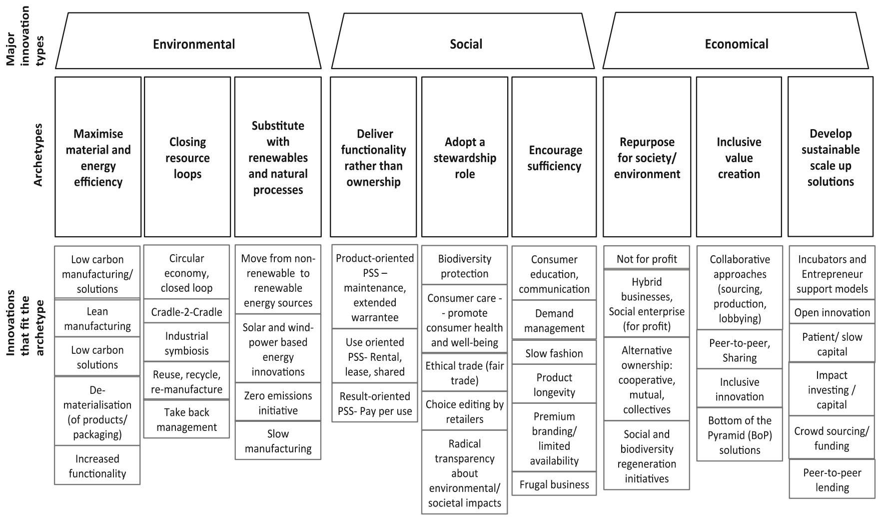

Fig. 1 Sustainable business model archetypes. Developed from [15]

2.2 *Business Experimentation*

Business experimentation is a process focused on 'deliberate learning by doing'. Business experimentation is most well-know as a concept in start-ups. For example, the lean start up approach emphasises the need for iterative approaches to explore possible value propositions [16, 17]. Weissbrod and Bocken [4] describe experimentation as a key avenue for accelerating change for sustainability in any type of organisation—not just start-ups. They emphasise the method of experimentation by means of a case of a large international retailer.

Business experimentation is inherently set in the realm of the social and so differs from experimentation in natural sciences, where regularities are sought from controlled situations so that generalisations can be developed. In contrast, business experimentation is context-sensitive and aims to either explore the diverse possibilities that a business could create value from, or understand what works in which particular situations [18].

Business experimentation is a systematic approach to identifying, testing and learning about value creation strategies that could be adopted by a business, in this case in response to the looming unsustainability crisis. Business experimentation is about establishing key 'hypotheses' or assumptions about the future business to 'test' [17, 19]. This can include, for example, questions around whether customers want to use a certain payment method, or whether there is a demand for a certain service or product in a particular location.

All experiments require funding and resources and in a world where many businesses rely on marginal revenue streams these experiments may be seen as unnecessary if the benefits are perceived unlikely to outweigh costs in the short term. Experiments should thus be as cheap to conduct and test as possible, allowing many possibilities to be explored and learned about before embarking on more intensive pilot programmes or changing the organization business model. As such, experiments establish learning that may determine the content of more resource intensive pilots.

In this paper, it is argued that experimentation is not only a helpful approach for start-ups, but also for large companies wanting to gradually change their business models for sustainability.

2.3 Research Gap: Sustainable Business Model Experimentation

The area of sustainable business model innovation has received significant traction in the academic literature [5–7, 11, 15, 20, 21] and more popular press [22, 23]. However, there is a discrepancy between sustainable business model innovation in start-ups and business model innovation in large organisations. It appears that the most inventive potentially sustainable business model innovations, such as home and car sharing, originate from innovative start-ups [24]. However, in this paper it is argued that there is a real opportunity for large businesses to experiment in similar ways to start-ups to become more sustainable, within the boundaries of the existing project teams and without setting up separate ‘skunk works’ or ‘sandpits’.

Whereas business model innovation for sustainability can be impactful, it is also challenging and can be slow. Business experimentation can be an important avenue to create more business model innovation. Whereas sustainable business model innovation and experimentation are closely linked, experimentation is viewed as a process and method to achieve greater levels of innovation in the business model. As such, it is viewed as a method to achieve more radical changes to business models. This paper recognises the importance of learning across start-ups and mature established businesses. Business experimentation as an approach more conventionally known to start-ups is positioned as a key method to accelerate change for sustainability in business but also more generally.

3 Method

This research addresses the following questions: What could business model experimentation for sustainability look like? How can it help drive positive change for society and the environment?

This research aims to investigate a contemporary issue in its real life context. It uses a multiple case study design [25] where conclusions are drawn across a number of cases. The unit of analysis is the organisation’s business model.

The cases observe experimentation within the organisations' business models in order to identify patterns for future research in this field. Two particular areas were determinants for including a business in this paper. Firstly, we identified businesses that changed their B2C product ownerships due to the desire to close resource loops. Secondly, the businesses had some communicated success in changing consumer behaviour. The necessity for customer development is a key component of the lean start-up approach [16] and we were looking for how start-ups and mature businesses conducted customer development in order to pursue a sustainability goal to close resource loops. The aim is to build knowledge for companies to start experimentation with their business models to accelerate the uptake of sustainability in business.

This research investigates the following cases (Table 1). Both start-ups and mature large companies were chosen, partially because of availability of public data, but more importantly, to highlight the opportunities and differences for both type of companies. For example, through experimentation, start-ups might quickly transform their entire business model, whereas experimentation in larger organisations can facilitate the co-existence of multiple business models and set in motion a gradual change to a new business model for the entire company.

The case study data is drawn from publicly available information: company websites and reports. In the case of 'Clothing retailer A', the information is drawn from conference proceedings [4]. All the case study businesses self-identify as 'sustainability leaders' in their publicly available information.

The case study information was reviewed with the research questions of this paper in mind: What could business model experimentation for sustainability look like? How can it help drive positive change for society and the environment? Information of relevance to answering the questions was summarised in writing, with a focus on diversions from the existing business model. These diversions—or 'pivots'—had to be driven by an explicit sustainability goal.

Table 1 Cases observed in this research

	Company	Type of business	Maturity	Sustainable business model archetypes
1	Gazelle	Consumer electronics—buy and sell	Start-up	Closing resource loops
2	Yerdle	Sharing economy model	Start-up	Inclusive value creation, closing resource loops
3	Mud Jeans	Clothing manufacturing and retail	Start-up	Closing resource loops, functionality, not ownership
4	Bugaboo	Manufacturing—baby strollers	Mature large company	Closing resource loops, encourage sufficiency, functionality, not ownership
5	Clothing retailer A (anonymous)	Clothing manufacturing and retail	Mature large company	Closing resource loops, encourage sufficiency

4 Results: Cases

This section includes a high-level illustrative view of the companies in question in order to see the particular changes or 'pivots' they have taken in their business model innovations.

4.1 Case Overview

Gazelle (gazelle.com) was founded in 2006 and starts its operations in 2007 in the area they refer to as 'reCommerce'. Originally it was focused on merely collecting smartphones in return for cash to the consumer. Phone manufacturers and network operators have since widely adopted the practice of buying back and trading in old handsets to recover valuable phone components. Hence, since 2014, Gazelle have started their own reselling branch, where they resell certified refurbished phones [26]. The company moved from partially closing resource loops (collecting phones), to seeking to more fully close loops by reselling refurbished phones.

Yerdle is an online sharing platform with its own currency. Its business model focus is on inclusive value creation and closing resource loops. While initially intended as a more offline neighbourhood-based sharing platform, they have made three key changes based on their original experiments: a move to 100 per cent to mobile; introducing 'Yerdle credits' to reward sharing, opening up the sharing marketplace more broadly beyond Facebook friends [27]. Whereas critics view the move to a sharing currency as an inhibiting factor to sharing, it can be argued that this approach can help scale up 'sharing' to a national rather than local level (e.g. in contrast to the US-based Craigslist 'free stuff' section, mainly catering for local sharing; [28]).

MudJeans is a forward-looking clothing business aiming to reduce clothing waste through the way business is done (mudjeans.eu). Initially, its aim was to lease jeans in order to facilitate reuse and recycling thus pursuing the business model 'functionality not ownership'. Because of low customer traction and practical issues associated with this option, it reverted to a deposit system, where you '[s]end your jeans back when you don't wear them any longer' [29]. However, at the time of writing, it is reconsidering a leasing option again. Materials are reused and upcycled into new clothing pieces.

Bugaboo describes itself as a mobility company [30]. It designs and manufacturers baby strollers. The design is aimed to be durable and long-lasting. Because products are designed with a long lifetime in mind, there was an opportunity in prolonging the useful product lifetime. As a new sustainability proposition, Bugaboo introduced its "Flex Plan", in short to give people access to the functionality of the baby stroller [31] without ownership and the flexibility to change strollers if needed. As a separate offering not part of its 'normal' sales channels, it can be an interesting way to gauge interest with such new business models.

Table 2 Case overview

	Company	Type of business	Maturity	Pivots and innovations
1	Gazelle	Consumer electronics—buy and sell	Start-up	From electronics buy-back, to buy-back + refurbish, certify and resell
2	Yerdle	Sharing economy model	Start-up	From online/offline platform, to wide online presence and developing its own value currency
3	Mud Jeans	Clothing manufacturing and retail	Start-up	From leasing jeans, to selling and a deposit system, back to leasing
4	Bugaboo	Manufacturing—baby strollers	Mature large company	Set up a leasing option in addition to selling baby strollers
5	Clothing retailer A (anonymous)	Clothing manufacturing and retail	Mature large company	Set up business model experiments (e.g. service innovations) in addition to selling clothes

Clothing retailer A is already a sustainability leader in its field [4]. In 2014, it set a radical goal to reduce clothing waste to zero [4]. Within this context, it started a business model experimentation process around 'closing resource loops' and 'encourage sufficiency' by seeking to maintain the highest form of the value of clothes over time [4]. While the experiments have gained traction and interest throughout the organisation, it remains challenging to run experiments in parallel to 'business as usual' [4]. Employees whose time has been freed up to work on the experiments are seen as essential to the business model innovation [4].

4.2 Cross Case Analysis

The cases have provided a variety of business model experiments and pivots. Table 2 summarises the cases. Whereas the start-ups have pivoting towards entirely new business models, in the more mature businesses, the new business models are co-existing with the existing ones within the boundaries of the existing organization.

5 Discussion and Conclusion

What could business model experimentation for sustainability look like? This paper shows that start-ups as well as large mature businesses have started to adopt the approach of business model experimentation for sustainability. While start-ups have transformed their entire business models, this paper shows the co-existence of multiple business models in larger organisations.

How can business experimentation help drive positive change for society and the environment? Each of the businesses in our mixed start-up/incumbent firm sample of cases has a clear business purpose for sustainability. The respective websites each show the ‘sustainability proposition’ of the new business proposition. The organisations investigated have a clear environmental positioning (mainly closing resource loops) to start, while others are also tapping into the more social aspects (e.g. Yerdle and sharing). Start-ups can use business experimentation to identify the most promising and disruptive business model in the market. Incumbent organisations can use business experimentation to develop sustainable value propositions. In this way, they can gain confidence to gradually pursue further sustainable business model changes to set in motion the gradual change to a (triple bottom line) sustainable business.

Large incumbent businesses can learn from start-ups: they can gain learning from experiments, before employing large-scale pilots. Experiments can be a good way for large incumbents to start mirroring the agility and (resource scarce nature) of a small start-up organisation. Whereas resource scarcity exists in both start-ups and large organisations, the nature of the scarcity would differ: start-ups might lack the money, whereas large organisations might lack committed resources and time. In both cases, experimentation can be a fruitful avenue. In the future, it would be interesting to follow the impact of start-ups and large businesses and analyse how one business model can start to dominate the other.

This paper only scratches the surface of the broad and potential impactful research area of business model experimentation for sustainability. Business model experimentation (building on ideas of the lean start-up [16, 17]) for start-ups and mature businesses is viewed as a powerful future research avenue to accelerate change in industries. The authors recommend that large businesses find inspiration in start-up business experimentation methods to develop sustainable business models. This may be linked to ambidexterity as an organizational capability in large businesses. Future work could include in-depth cases and tools and methods to advance the work on business model experimentation for sustainability. These tools and methods need to set business model experimentation in the context of well-established corporate innovation methods.

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Design of Indicators for Measuring Product Performance in the Circular Economy

Percy Griffiths and Steve Cayzer

Abstract This paper explores measurement of product performance with respect to circular economy principles. Potential indicators are assessed, with special attention given to questions such as: the variables that should be measured; how these variables should be assessed; and in which format they should be presented. The resulting considerations are used to develop a prototype whose design is informed through feedback from Circular Economy experts. The prototype uses a points-based questionnaire which converges into a simple final result with minimum and maximum limits. The selected approach is critically appraised, and its utility for decision-making discussed. The strengths include: ease of use; simplicity; speed; and an effective metaphor for the diffusion of circular economy principles. The limitations include: the opaque and potentially misleading nature of a single metric; superficial engagement with decision making; and the reliance on context specific assumptions. Future developments could include refining the approach to encourage deeper reflection, and generalization of the approach to different industry sectors or sustainability frameworks.

Keywords Circular economy · Metrics

1 Introduction

The Ellen MacArthur Foundation (EMF) has been set up to champion a notion of a "Circular Economy" (CE). According to the EMF [1] the CE contrasts with the dominant economic paradigm of a "Linear Economy" (LE); a chain of activities dependent on the extraction of raw natural resources. CE has significant traction,

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with explicit policy in China [2] and Europe [3]. The EMF has attracted global partners including Google, Unilever and Renault [4] thus confirming its status as an integrative and leading force around the CE topic.

1.1 Theoretical Roots

Although the EMF is relatively new, the CE concept (and its theoretical roots) are not. Circular thinking has a long history [5] and the analogy of industrial metabolism [6] is well established. CE models are built on the foundation of decades of research in such fields as Industrial Ecology [7], the Performance Economy [8], the Blue Economy [9] and Cradle to Cradle [10]. The EMF explicitly acknowledges these schools of thoughts in its 'CE Principles' [1]. The metrics presented in this paper are thus intended to have relevance for the underlying models implicated by the use of the EMF framework.

It could be argued that the EMF approach is somewhat euro-centric; Gregson and Crang [11] argue that circular economies (plural) should be viewed in a global context. Using the notion of value recovery, they differentiate between hi-tech, capital intensive approaches (promoted by the EMF interpretation) and labour intensive approaches; arguing that the latter may serve a wider range of global markets.

1.2 The EMF Notion of a Circular Economy

Figure 1 depicts the EMF conceptualisation of a circular economy [1], suggesting the preservation of value, or *revalorization* [12] through activities like reuse, refurbishment and remanufacturing.

EMF suggests a number of approaches for revalorization through its CE principles [1] including:

- Design out waste; treat waste as a resource;
- Design for disassembly; standardise and modularise;
- Select feedstock materials based on circularity potential;
- Promote resilience through diversity;
- Obtain energy from renewable sources;
- Think in 'systems' and cascades.

Some of these concepts are rather broad and are subject to multiple interpretations; some details of the particular EMF perspective (particularly around systems thinking) can be found in [13].

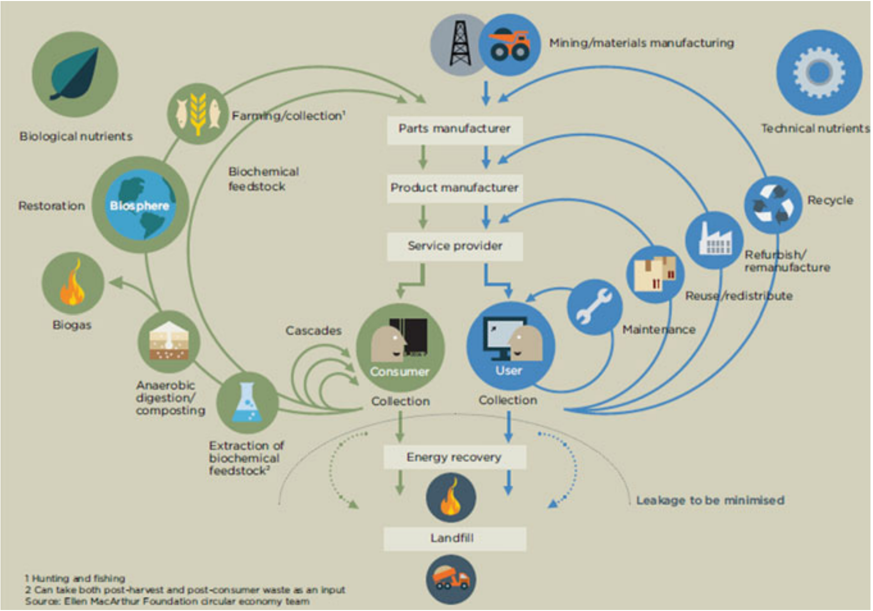

Fig. 1 The EMF conceptualization of a circular economy, showing two types of feedback loop: technical and biological [1]

1.3 Circular Economy Indicators

In order to assess whether CE principles are leading to meaningful change, it is necessary to develop a measurement system [2]. Indicators have the "*ability to summarise, focus and condense the enormous complexity of our dynamic environment to a manageable amount of meaningful information*" [14]. Church and Rogers [15] refer to indicators as "*means to measure change*" so they can be used for managing the transition to CE. CE indicators could work to: inform policy; promote literacy around the CE topic; enable new quality standards; and compare businesses for sustainability investment indexes and markets. However, Beratan et al. [16] warn that indicators must be connected to decision-making and implementation. Thus indicators do not in themselves achieve a successful transition to a CE, but are an important tool for aiding progress towards this goal.

1.4 Existing Circular Economy Indicators

CE indicators are at an initial stage of development [17]. Perhaps the most high profile example comes from China, where the government applies well-known assessment methods to measure the performance of their CE policies (e.g. Life

Cycle Assessment, eco-efficiency and carbon footprint). While illustrating the political impact of CE thinking, Geng et al. [2] acknowledge that these indicators "*weren't designed for the systemic, closed-loop, feedback features that characterize CE.*"

Another example comes from Europe, where the European Commission Environment Program partnered with the EMF and Granta Design on the LIFE + Project [18]. The LIFE + CE indicators include a "Material Circularity Indicator (MCI)" as well as complementary indicators for toxicity, scarcity and energy. MCI has now been incorporated into a commercial offering. The development of the MCI included a pilot project with the home improvement retailing company Kingfisher, testing the approach on real products. The resulting prototype is called "Kingfisher Circularity Calculator" (KCC) on which the prototype described in this paper is built.

2 Methodology

This paper attempts to answer the research question: What are suitable characteristics of indicators for measuring the performance of products within the EMF Circular Economy model? In order to address this question, this paper takes the following approach: the EMF CE principles are used as a base from which relevant and measurable variables are derived, together with ideal targets. The KCC is extended into a CE indicator prototype (CEIP), the design of which is based on a literature review supplemented with a first round of 45–60 min long interviews made in June, July and August 2014 with subjects shown in Table 1. These interviewees are chosen on the basis of their relationship with, or interest in, CE and their diverse sectoral backgrounds.

The CEIP was designed in MS Office Excel and tested with a panel of potential users (P2, P3 and P8 from Table 1) via a second round of interviews and questionnaires. The CEIP approach is also critically evaluated against these questions:

- Is this use of a single metric appropriate?
- Does the metric reliably indicate improved environmental outcomes?
- Does the metric lead to improved decision making?

3 Results

The interviewees identified fifteen possible variables which could be linked to EMF CE principles. These were grouped according to the lifecycle stages of the product to facilitate the understanding of the user (Table 2).

The CEIP was designed by defining a question corresponding to each variable, taking or amending these from the KCC where appropriate. Each question has

Table 1 Interviewees participating in Phase 1 of the research

Participants					
#	Name	Organisation	Charge	Profile	Origin
P1	Ken Webster	Ellen MacArthur Foundation	Head of Innovation	More than 15 years of experience in Environmental topics. He is the main curator of CE model in the Foundation	UK
P2	Chris Tuppen	Advancing Sustainability	Founder	More than 20 years of experience in Sustainability topics and 50 published papers. Fellow of the Royal Society of Arts, member of the Institute of Physics	UK
P3	Michael Whitley	3 MW Circular Economy Consultancy	Founder	Previously responsible for Supply Chain and Business Model Strategy, Hewlett-Packard	UK
P4	Ana Pereira	Grante Design	Project Manager for Education and Research	PhD in Biological Engineering, MSc Energy and Environmental Engineering. Member of the team that worked in the development of the MCI	UK
P5	James Walker	Resolver	CEO	Previously Head of Innovation of Kingfisher plc. And Steering Committee member of the Technology Strategy Board	UK
P6	Carlos Zuzunaga	McKenzie	Associate	Bachelor in Economics and MBA from Columbia Business School US. More than 7 years of experience in business consultancy	Peru
P7	Ignacio Arrospide	AFP Integra	Investment Manager	Bachelor in Economics and MBA from Kellog School of Management at Northwestern University US. More than 10 years in investment management	Peru
P8	Anonymous	Technology and Innovation Consultancy firm	Technology and Innovation Consultant	More than 25 years of work experience in R + D departments of major global technology brands. Major studies in Microelectronics and Physics	UK
P9	Andre Fourie	SAB Miller	Senior Manager, Environmental Value	More than 15 years of experience in Sustainability Topics in the Beverage Industry	UK

All interviews were conducted by skype with the exception of P1 and P9 which were face to face

Table 2 Questions used in the CEIP: the variable they measure; the rationale for including them; their weighting; and relationship to CE principles

Lifecycle stage	Question	Variable measured: rationale	Points	Associated CE principles
Design/redesign	Is the product made from recycled/reused material?	**Material Selection—Use of Recovered Material**. The use of reused or recycled materials reduces waste, demonstrates social responsibility and can help to ensure continuity of material supply	20	Material Selection, Cascades Thinking
	*Is the product lighter than its previous version?	**Material Selection—Dematerialization**. A good circular design demands less material for the same performance and quality	2	Material Selection
	~Is there a complete bill of materials and substances for the product?	**Material Identification—Presence of Bill of Materials**. A complete bill of materials and substances provides the information required to plan for the recapture and re-use of component materials and enables the management of hazardous substances	5	Material Identification
Manufacturing	*Is there a complete bill of energy for the manufacturing process?	**Energy Identification—Presence of Bill of Energy**. A complete bill of energy provides the information required to plan for the energy consumption and efficiency of manufacturing processes. It also contribute to the shift for using more renewable energy sources	10	Energy Identification

(continued)

Table 2 (continued)

Lifecycle stage	Question	Variable measured: rationale	Points	Associated CE principles
	*Is there a complete bill of solid waste for the manufacturing process?	**Manufacturing Waste Management**. Waste must be avoid in a CE and it must be treated as "food" for other processes. The waste of one process must be the resource for another process. This decreases the pressure and impacts of waste to the environment	15	Waste Management
Commercialisation	What packaging is being used?	**Product Packaging**. The impact of the packaging of the product or service has been reduced or eliminated with any packaging that has been used being clearly labelled to allow for effective recycling	5	Cascades Thinking, Materials, Waste
	What is the product's warranty?	**Product Lifetime Extension—Warranty**. Extended product guarantees that minimise the need to purchase replacement products can help to enhance our reputation for providing high quality, durable products	10	Cascades Thinking, Waste
	~Is there a rental option for the product?	**Product Access—Rental Schemes**. Rental schemes beside acquisition enables customers to access higher quality products and materials without having to purchase the product themselves	15	Diversity

(continued)

Table 2 (continued)

Lifecycle stage	Question	Variable measured: rationale	Points	Associated CE principles
In use	*Can the usage status and identification of the product be established?	**Product Lifetime Extension—Usafe Status and ID**. Knowing the usage status and the identification of the product contributes to plan maintenance actions before a malfunction happens. Thus, the lifetime of the product is extended.	15	Cascades Thinking, Waste
	Can the product be repaired?	**Product Lifetime Extension—Repair Options**. Product lifetimes can be extended where products have been specifically designed for easy repair. This helps to retain custom and enhance our reputation for providing quality products and services	5	Cascades Thinking, Waste
	*Can the product be reused?	**Product Lifetime Extension—Reuse Options**. Product lifetimes can be extended where used products have been designed to be traceable and their usage status can be easily established. Second hand markets development fosters products to find new users and extend their lifetime	10	Cascades Thinking, Waste
	Does the product reduce waste through its use?	**Waste Reduction**. Products that reduce waste facilitate the CE by enabling other products to become more circular	5	Waste Reduction

(continued)

Table 2 (continued)

Lifecycle stage	Question	Variable measured: rationale	Points	Associated CE principles
End of use	"What take-back scheme is available for this product?	**Product Recovery—Availability of Take Back Schemes**. Take-back schemes enables customers to dispose of their unwanted products and provide a mechanism for the recapture of materials and their introduction into the supply chain	15	Cascades Thinking, Materials, Waste
	Is the product separated out from other products at the end of its life?	**Product Recovery—Segregation**. The products recovered via take- back schemes are segregated properly and can be used to provide raw materials for the manufacture of new products. This reduces the risk of material scarcity and pricing fluctuations in the supply chain	10	Cascades Thinking, Materials, Waste
	Are the product's materials passed back into the supply chain?	**Product Recovery—Product's Materials Reintroduction**. Reusing or recycling a high proportion of the reclaimed material drives the development of a CE	10	Cascades Thinking, Materials, Waste

Questions prefixed with an asterisk (*) are new; a tilde (∼) denotes one that has been amended from the KCC version

multiple answer options, with weightings informed by the expert interviews. The questions are grouped by lifecycle stage, with a single aggregated score showing the "circularity" of the product. The CEIP was designed in MS Excel due to its high level of diffusion across multiple business sectors. The CEIP includes a Summary tab, with a "Questionnaire" tab containing the fifteen questions. Figure 2 presents snapshots of the CEIP.

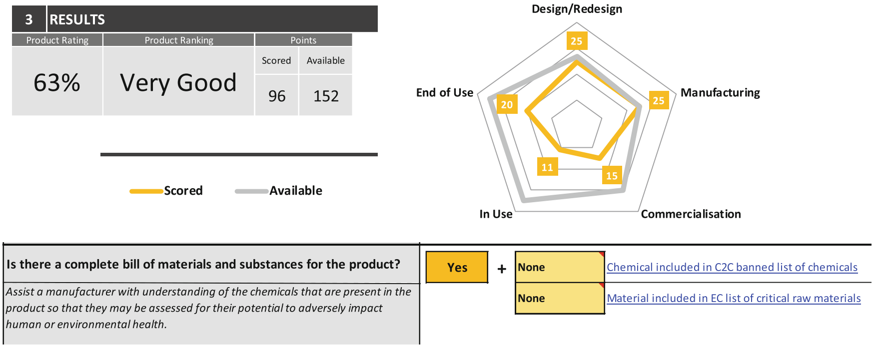

Fig. 2 Selected part of the CEIP interface. The overall score (*top left*) is expanded to a spider diagram (*top right*) showing circularity across different parts of the lifecycle. The 'bill of materials' question (*bottom*) can be answered with a simple yes/no, but extra bonus points are awarded where the bill of materials does not include substances on the nominated critical lists

3.1 User Feedback

The CEIP is based on the KCC, but there are some differences. As well as the 5 new questions, some answer options include the concept of "bonus points". The main objective was to show the companies additional ways to improve. The CEIP has separate pages and clearer instructions. The lifecycle stages and the variables are included next to each question to facilitate the recognition of what it is being assessed in the product. The following comments were made by interview participants about the CEIP:

- The CEIP is '*easy to follow*' (P3) "*far more comprehensible*" than the KCC (P8).
- The CEIP could be used "*as a training exercise for engineers*" (P3) and "*to understand the levers for working on circularization*".
- P3 commented that the CEIP could be useful "*as a checklist*" (P3) and could be extended to "*a comparison of 2–3 product versions on one page*". P2 cautions that Q4/5 are "*good to include for completeness*" but may make it "*more difficult to make an assessment*".
- There were some comments on hidden complexity, for example P2 noted that "*lighter may mean more carbon intensive materials and/or materials that are more difficult to recycle*".
- P3 also commented that the tool is best suited for incremental changes and therefore less suited to "*throwing away your business model and starting again*", and may need a "*future evolution*" to be more service-focused.

4 Discussion

4.1 Comparison with KCC

The interview feedback showed a preference for the CEIP interface over the KCC. The CEIP was not compared with the MCI, which is not publicly available. Since the MCI builds on KCC the findings are likely to be similar. One of the interviewees was part of the LIFE + Project [18] which developed the MCI. In their interview, he was positive about the CEIP, specifically the question "*Can the usage status and identification of the product be established?*" suggesting this as an area for further development.

4.2 Use of Single Metric

It seems counterintuitive to use a single metric for a concept like circularity which is clearly multi-faceted. Product circularity depends on the lens through which it is viewed: impact measure (energy, CO_2, equity); lifecycle stage (manufacture, use, 'end of life'); activity type (design, marketing, refurbishment). Gasparatos et al. [19] argue that "*no single perspective can provide an adequate vision*". They point out that aggregated metrics imply substitutability between dimensions. An alternative would have been a range of single valued metrics, perhaps with criteria more directly linked to sustainability (e.g. CO_2 emissions). To some extent the CEIP does this by separating the impacts into lifecycle stages. The intention is that users are exposed to CE complexity gradually, and can drill down to the different stages as required. Further refinement is possible, including consideration of the interrelationships between dimensions [19].

A single metric does have the advantages of communication and simplicity. An analogy is the "Inclusive Wealth Index" [20]: a single metric covering economic, social and natural capital. It could be argued that circularity itself has a similar function; an umbrella term to simplify the underlying concepts and aid their diffusion.

4.3 Does the Metric Reliably Indicate Improved Environmental Outcomes?

There are two discussion points here: firstly, do the EMF CE principles reliably lead to better environmental outcomes; and secondly, does the CEIP successfully indicate adherence to the EMF CE principles?

With regard to the former, the EMF CE model appears to take as axiomatic that inner loops preserve most value. However, there are important questions to be asked about efficiency [12] and cultural attitudes to ownership [21]. In his comprehensive review Tukker [22] states of that product service systems are "*not the sustainability panacea*"; for example, users of leased products tend to take less care of them. A study by Tabone et al. [23] illustrates another difficulty. They derived a variety of metrics from green chemistry principles (some of which are similar to the EMF principles). These metrics are aggregated into a single score, which does show an overall qualified correlation with lifecycle impact. However, the lifecycle impact of biopolymers is generally underestimated and that of petroleum polymers overestimated.

With regard to the latter, a design decision was to use a multi-metric view covering different CE dimensions (material, energy or waste). Predefined options, including 'ideal circularity', are derived from EMF CE principles. These options depend on a number of assumptions which may not be appropriate for the product in question. For example, the question about recycling takes no account of whether the loop is closed (i.e. returned to the original manufacture). The values for the scores (weighting), although informed by expert interviews, could be sensitive to context. In addition, the selected variables were designed mainly for products in the Home Improvement sector, and the CEIP is not assumed to be reliable for products from other industries.

4.4 Does the Metric Lead to Improved Decision Making?

The preceding discussion suggests that the CEIP should not be the sole source of decision making, and that the circularity score is taken as indicative rather than definitive. However the tool may improve decision making through more widespread diffusion of circular thinking. To this extent ease of use is a crucial requirement. The prototype has been designed for an intermediate user who should have reasonable knowledge on: CE model; the product that is being assessed; and MS Excel. The most challenging requirement could be the second one because it demands a deep understanding of the performance and characteristics of the product in all its lifecycle stages. Participant 2 gave the following comments about this challenge: "*I think the biggest challenge is actually knowing or finding the data to put into the tool ... complicated supply chain(s)... what happens to products at end of life*".

This challenge could be seen as an advantage as it encourages users to engage more deeply with circularity considerations for their product. Participant 3 highlights this potential: "*training... engineers, and other functions, to understand the levers for working on circularisation.*". This may be more important than the raw circularity score which may have limited direct use. As participant 6 commented "*right now those indicators won't be useful because our services are customer-driven and they ... don't ask for [CE] evaluations...*". That is not to say that the output could not, in principle, be useful in the future—Participant 6 adding "*We also could use them [for] industry benchmarks*". Participant 7 remarked: "*They can* *help us to evaluate non-financial [and] long term aspects*". If this route is taken, then it is likely that more work will be needed to signpost the indicative nature of the tool's output.

4.5 Future Work

Future work could include developing CE indicators for different industry sectors and product types. Even with the same CE variables, the questions that evaluate those variables, their weighting—and the optimal circularity options—could be varied depending on the context. According to Connett [24] and WRAP [25] the sectors that provide a suitable environment for applying those indicators are those with middle and long lived products: Automotive; Electricals and Electronics; Clothing and Textiles; and Food and Drink. Future CE tests should also enable comparison between products.

As discussed above, use of a single metric has clear advantages for simplicity and diffusion. However, more complex or ambiguous metrics may force users to engage more deeply with sustainability decisions, a position reminiscent of Morozov [26] in his critique of frictionless "solutionism". This is a topic that deserves further attention.

5 Conclusion

The EMF Circular Economy (CE) model is an emergent paradigm for managing resources in a more efficient way to create a regenerative economy that has positive economic and environmental impacts. CE strategies can create resource efficiency, promote renewable energy and move towards zero waste. Yet transitioning from a Linear to a Circular Economy presents several challenges. The one tackled here is the need to measure CE product performance through indicators. CE indicators would allow businesses to monitor the implementation of CE strategies. Consequently, the research question was established: What are the possible characteristics of indicators for measuring the performance of products within the EMF CE model?

In order to probe this question, a prototype of CE indicators (CEIP) was developed. A multi-measure approach is taken, with a single aggregated metric for each lifecycle stage. This approach has several advantages: speed, simplicity; ease of diffusion; comprehensible metaphor. However there are some limitations and challenges: hiding of complexity; potentially misleading results; superficial engagement with decision making; and the reliance on context specific assumptions. The reaction from CE experts is largely positive but further development is required, particularly the tradeoff between simplicity and engagement; and consideration of other industries.

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An Integrated Product Development Approach to Improving Sustainability Using Simulated Experiments: Manufacturing Case Study

Joseph Axiak, Paul Refalo and Emmanuel Francalanza

Abstract Sustainable Manufacturing (SM) and Integrated Product Development (IPD) have both been identified as important drivers of an organization's competitiveness and agility. However, their multi-faceted nature requires organizations to make manufacturing decisions without compromising any of the pillars contained within SM (economy, environment and society) and IPD (product, production and business). Achieving the aims of both IPD and SM increases this complexity even further and results in the need for high-level tools and systems for decision-making. This paper presents the use of digital factory simulation, as a tool to support the integrated development of sustainable products and processes. To evaluate this approach, a case study involving an existing manufacturing line was performed. The aim of the study was to generate a platform for the testing of experimental scenarios giving predictive results on the impact of IPD decisions on the manufacturing sustainability of the process. Together with the limitations and difficulties encountered, the validity and feasibility of using digital factory simulation for the integrated development of sustainable products and processes is discussed.

Keywords Sustainable manufacturing · Integrated product development · Simulation

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1 Introduction

In 1987, The World Commission on Environment and Development defined Sustainable Development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [1]. Also, in 1987, Barbier suggested that any process of development will have an impact on the biological or ecological resource aspect, the economic aspect and the social aspect of any system [2]. Based on these three divisions, Elkington developed the triple bottom line (TBL) concept in 1998, which calls for corporations to consider and monitor their overall impact on the environment and society, as well as its financial gains, creating a "bottom line" for each [3]. In the same year, Robinson and Tinker developed this concept further by stating that an organization, or governing body, can only make manufacturing decisions with no compromise across the economy, environment and society by integrating decisions [4].

Twelve years later, Hahn et al. argued that even through the mainstream of the literature theorize on achieving economic, environmental and societal growth simultaneously, the multi-faceted nature and complexity of the task implies that trade-offs and conflicts in corporate sustainability are still the rule rather than the exception [5]. This indicates that high level tools are required in order to simplify the complex, and aid decision-making ensuring no trade-offs to the three facets of sustainable development.

1.1 Sustainable Manufacturing

In modern times, sustainable manufacturing is of paramount importance to industry. As stated by Wyckoff "[sustainable manufacturing] is no longer just nice-to-have, but a business imperative" [6]. Increasing pressure towards sustainable development worldwide has been a driving force for companies to focus on balancing environmental protection, economic and social development. Following a series of corporate scandals including oil spills and sweatshop labor, organizations are expected to be more accountable and transparent. In other words they are expected to conform to corporate social responsibility [7].

1.2 Integrated Product Development

Integrated Product Development (IPD) is an idealized model for concurrent product development which integrates the three main disciplines of marketing, design and production. As discussed by Hein and Andreason, the main aim of the IPD approach is to have a successful business, therefore satisfying the customer's requirements [8].

1.3 Manufacturing Simulation

Modelling and simulation technologies hold tremendous promise for reducing costs, improving productivity and quality, and shortening the time-to-market of manufactured goods. Kibira and McLean state that manufacturing simulation is mostly used to provide support tools to facilitate manufacturing decision-making. Typically simulation studies will involve the modelling of particular aspects of current operations and the testing of scenarios, to predict the impacts of the proposed changes to the operations [9]. McLean and Leong discuss that simulation technology has become a top research priority that promises high gains. This is driven by the fact that manufacturing systems, processes and data are growing more and more complex, further increasing the need for high-level tools such as simulation [10].

1.4 Research Gap

Both Sustainable Manufacturing and Integrated Product Development have been identified as needs for an organization to increase competitiveness and agility in today's fast-changing industries. Both concepts indicate a certain level of complexity due to their multifaceted nature, requiring the use of elaborately designed tools and methodologies to obtain them, especially when combining the two. Refalo suggests that such a goal could be coined as Sustainable Integrated Product Development (SIPD) [11].

Developing further from Elkington's concept of TBL (Triple Bottom Line), SIPD's ultimate goal would be to consider a Quintuple Bottom Line (QBL), ensuring that manufacturing decisions would not compromise any of the five sectors, i.e. Product, Production, Business (which is linked with Economy), Environment and Society.

Digital factory simulation during decision making has shown vast improvements in efficiency and cost-effectiveness, as well as reducing time-to-market [12]. An opportunity is therefore identified in using Software Simulation as a tool for Sustainable Integrated Product Development, as well as presenting a number of challenges.

2 Methodology

In order to address this opportunity, a typical software simulation exercise was conducted with the aim of investigating how such a tool can be used for Sustainable Integrated Product Development decision-making. The concept was to generate a

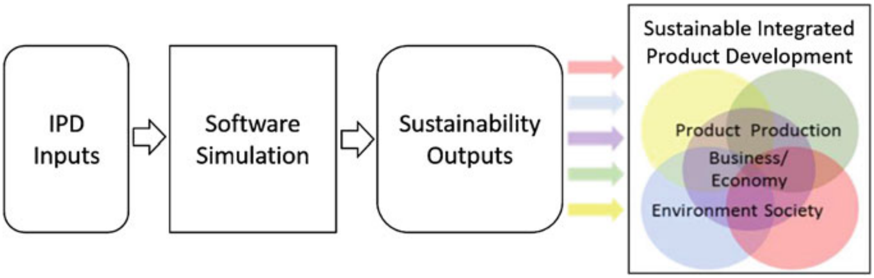

Fig. 1 Proposed methodology for using Simulation as a tool for SIPD

simulation model which answers IPD questions with outputs related to the three pillars of sustainable manufacturing (environment, economy, society), shown in Fig. 1.

A manufacturing line of a polymer product was chosen as a case study, and a simulation exercise was performed. Based on methodologies investigated from various literary works, with significant influence from Balci's methodology, the following framework was followed during the simulation case study.

The study started with efforts on understanding the system, followed by the identification of the simulation goals. To be able to explain the manufacturing line in detail, the real line was observed, and a value stream map was constructed as a conceptual representation of the current state of the manufacturing line. Next, a virtual model was constructed based on the conceptual representation using the software Tecnomatix Plant Simulation by Siemens, a software package designed specifically for the modelling, simulation and optimization of manufacturing, as well as process planning [13]. It is an ideal tool for the manufacturing line under study specifically due to its capability to model and simulate working shift systems, transportation systems, participants in the work and their assigned tasks, conditions such as working, pausing, waiting and so on.

The model outputs were designed to be in the form of sustainability Key Performance Indicators (KPIs), divided in three groups relating to environment, economy and society. Amrina and Yusof [14] suggest a comprehensive list of Sustainability KPIs, most of which could be suitable as simulation model outputs. However, not all the metrics were considered applicable for the study, and the list was reduced based on the applicability of historical data and available measurement methods at the manufacturing line under investigation. Whilst many more metrics could be used as simulation outputs, there would have been no means to validate and verify the output values, given the limitation in measuring such metrics at the real manufacturing line. A specific difficulty was encountered when attempting to select typical societal metrics such as job satisfaction and employee talent development.

In an attempt to include societal metrics, specifically related to Health and Safety, the distance walked by employees was measured throughout the duration of the simulation run. Whilst not providing much insight on the societal impacts of the manufacturing process, the distance walked by the operator may be directly linked to the fatigue experienced by the worker, or alternatively may contribute to a level of fitness resulting from the activity. Therefore the metric was chosen to at least shed light on the usability of software simulation for evaluating the impact a manufacturing decision would have on the employees.

The model was validated by analyzing its performance and its outputs, and comparing it to the real life manufacturing line, using the methodologies described by Sargent [15]. Table 1 compares the values on the simulation scorecard with actual values from the plant, showing a maximum variation of 8.42 %.

Law and Kelton discuss that a variation of 10 % is a widely accepted value during simulation modelling, making the developed model satisfactory for the case study [16]. The actual data from the plant was obtained from various sources including historical data, budgeted costings for labor, and cost of materials, consumption of subassemblies and raw materials, as well as direct measurements from the manufacturing line.

Having obtained a model representative of the real system, different scenarios were designed and run by changing the inputs. The scenarios included specific changes in product, production and business aspects, in order to ask IPD questions to the model. After running the scenarios, the results obtained were analyzed and documented, getting insight on the impact resulting from said scenarios [17–20].

Table 1 Validation Run Scorecard comparison with actual data

		Model	Actuals	Variation
Environmental performance				
1. Resource util.	(1) Energy utilization per unit	0.04444 kWh	0.0485 kWh	−8.42°%
2. Waste	(2) Solid waste generated per unit	4.534 g	4.701 g	−3.56°%
Economic performance				
3. Quality	(3) Scrap cost per unit	0.0315 €	0.0313 €	0.47 %
	(4) Reject rate	15.72 %	16.23 %	−3.13 %
4. Cost	(5) Overhead cost per unit	0.05071 €	0.0541 €	−6.33
	(6) Inventory cost per unit	10928 €	N/A	N/A
	(7) Unit cost	0.53854 €	0.5533 €	−2.66 %
	(8) Labour cost per unit	0.04538 €	0.0483 €	−6.08 %
5. Delivery	(9) Overall cycle time	4.33735 s	4.618 s	−6.08 %
Social performance				
6. Employee	(10) Daily kms walked per worker	1.994 km	N/A	N/A

3 Results

3.1 Scenario 1—Improving Machine Quality

In the first scenario, the quality performance of one of the machines was altered by changing the scrap rates of the machine. The current scrap rate of the case study which was studied is at 5 %. A series of scrap rates between 1 and 9 % were applied and the percentage variations obtained for each run are shown in Table 2.

Most significantly, there was a marked impact in environmental sustainability, as improving the quality of a machine results in a reduction in energy consumption and a reduction in solid waste. In terms of economical sustainability, there is an immediate benefit with a reduction in scrap costs, as well as creating a more profitable product overall. A slight negative impact is detected by the model in societal sustainability, due to the increased walking distance as manufacturing outputs increases with less scrap. Metrics for job satisfaction, employee morale, as well as corporate social responsibility would most probably improve with reduced scrap, but this is not visible from the model.

This scenario has shown, that by changing factors from the production and by extension, the production design, the simulation provided predictive results on the impact that this change would have across the Triple Bottom Line, and not only on environmental performance.

Table 2 Variations in scorecards for simulations with altered machine quality performance

	1 % scrap	3 % scrap	5 % scrap	7 % scrap	9 % scrap
Environmental performance					
(1) Energy utilization	−3.36 %	−1.72 %	N/A	1.72 %	4.18 %
(2) Solid waste	−40.57 %	−20.30 %	N/A	20.12 %	40.40 %
Economic performance					
(3) Scrap cost	−54.96 %	−27.51 %	N/A	27.32 %	54.79 %
(4) Reject rate	−21.88 %	−10.92 %	N/A	10.71 %	22.15 %
(5) Overhead cost	−3.47 %	−1.77 %	N/A	1.83 %	4.38 %
(6) Inventory cost	0.14 %	0.17 %	N/A	−0.12 %	−0.53 %
(7) Unit cost	−5.86 %	−2.84 %	N/A	3.39 %	6.74 %
(8) Labour cost	−3.49 %	−1.78 %	N/A	1.84 %	4.40 %
(9) Cycle time	−3.49 %	−1.78 %	N/A	1.84 %	4.40 %
Social performance					
(10) Daily kms walked	0.80 %	0.33 %	N/A	−0.40 %	−1.09 %

3.2 Scenario 2—Changing the Shift Pattern of the Loading/Packaging Personnel

In the second simulated experiment, the shift pattern of the packaging personnel was changed from a two-shift basis to a three-shift basis. This would imply an increment in wages, but the same labor hours dedicated to the process since the packaging process is not the bottleneck of the manufacturing. This was done in order to eliminate the buffers accumulating during the inactive night shifts. The scorecard obtained is shown in Table 3, with variation to the scorecard obtained in the Validation Run.

This scenario presents small changes in the economic pillar of sustainability by reducing Inventory Costs which was actually the target of this scenario, whilst increasing Labor Costs and Overhead Costs. Space is many times a commodity in a manufacturing environment, so dropping buffer sizes could justify the increased costs. Implementing such a change would only require shop floor employees to change their shift patterns, meaning that it would have no significant impact on the business aside from the increased labor cost. On the other hand, the simulation run presents no insight on the impact that the change would have on the employees, even though it implies a change in their lifestyles. This example gives an indication of the limitations of the simulation model obtained, as well as the difficulty in simulating societal considerations.

3.3 Scenario 3—Changing Stack Size of Bins

In the manufacturing line under study, material is transferred from one process to the next in bins, typically stacked in groups of six. For the third scenario, the stack

Table 3 Scorecard for Revised Shift Pattern with variation to Validation Run

			Variation
Environmental performance			
1. Resource utilization	(1) Energy utilization per unit	0.04443 kWh	−0.02 %
2. Waste	(2) Solid waste generated per unit	4.53562 g	0.04 %
Economic performance			
3. Quality	(3) Scrap cost per unit	0.0315 €	−0.01 %
	(4) Reject rate	15.77 %	0.32 %
4. Cost	(5) Overhead cost	0.05232 €	3.17 %
	(6) Inventory cost	10423.35 €	−4.62 %
	(7) Unit cost	0.54014 €	0.30 %
	(8) Labour cost	0.04699 €	3.54 %
5. Delivery	(9) Cycle time	4.33735 s	0.00 %
Social performance			
6. Employee	(10) Daily kms walked	2.002 km	0.36 %

Table 4 Scorecard for Reduced Stack Size with variation to Validation Run

			Variation
Environmental performance			
1. Resource utilization	(1) Energy utilization per unit	0.04443 kWh	−0.03 %
2. Waste	(2) Solid waste generated per unit	4.54412 g	0.22 %
Economic performance			
3. Quality	(3) Scrap cost per unit	0.0315 €	0.22 %
	(4) Reject rate	15.75 %	0.18 %
4. Cost	(5) Overhead cost	0.050S0 €	0.13 %
	(6) Inventory cost	8671.03 €	−20.55 %
	(7) Unit cost	0.53S70 €	0.03 %
	(S) Labour cost	0.04547 €	0.20 %
5. Delivery	(9) Cycle time	4.34508 s	0.20 %
Social performance			
6. Employee	(10) Daily kms walked	2.223 km	11.45 %

size of materials was changed from six to five bins, implying a material transfer yield decrease of 16.7 % (one-sixth). The scorecard for this run is shown in Table 4.

The scorecard achieved shows limited changes in the overall process performance but represents a great reduction in Inventory Cost, resulting from the reduced content of every stack. The only other significant change is an increase in the distance walked by the employees, resulting from increased movement of stacks due to the lower yield from each movement.

This analysis has revealed that a simple solution such as reducing the stack size actually signified a greater reduction in inventory cost than Scenario 2. Furthermore the labor cost of the product was not significantly altered, whilst in Scenario 2, there was a marked increase in labor costs due to the rearranged shift patterns.

The scenario implies a negative impact due to the increased fatigue experienced by the workers. However considering that such an improvement was obtained without altering the shift patterns, one could speculate that the impact on society is actually less significant, although this is not directly visible from the model outputs. The simulation does not provide enough insight on the societal impact and a deeper analysis would be required.

3.4 Scenario 4—Changing Product Characteristics

The fourth scenario proposed changing the dimensions of one of the components of the finished product, i.e. the tube length. The tube length is currently set at 145 mm and by changing its length, the functionality of the product is not altered. To test the effects of this change, several simulations were run with different tube lengths, the results of which are shown in Table 5.

Table 5 Scorecard variations for altered tube lengths

	100 mm	125 mm	145 mm	175 mm	200 mm
Environmental performance					
(1) Energy utilization	0.00 %	0.00 %	N/A	0.00 %	0.00 %
(2) Solid waste	−7.88 %	−3.50 %	N/A	5.25 %	9.63 %
Economic performance					
(3) Scrap cost	−2.03°%	−0.94 %	N/A	1.23 %	2.32 %
(4) Reject rate	0.00°%	0.00 %	N/A	0.00 %	0.00 %
(5) Overhead cost	0.00 %	0.00 %	N/A	0.00 %	0.00 %
(6) Inventory cost	−0.36 %	−0.06 %	N/A	0.39 %	1.46 %
(7) Unit cost	−2.35 %	−1.05 %	N/A	1.56 %	2.86 %
(8) Labour cost	0.00 %	0.00 %	N/A	0.00 %	0.00 %
(9) Cycle time	0.00 %	0.00 %	N/A	0.00 %	0.00 %
Social performance					
(10) Daily kms walked	−0.17 %	−0.06 %	N/A	0.23 %	0.53 %

Several changes across most metrics were observed. Reducing the tube length results in significant savings directly resulting from a reduced usage of raw materials, but also resulting in reductions in inventory costs and higher yields from raw material transfer, reducing employee fatigue as well.

This scenario is a perfect example of how an IPD question, with changes in product design, having an impact on the production as well as the business aspects, obtains sustainability metrics as outputs, across the economic, environmental and societal pillars. This can also be extended to include changes in other product details. However, many times these may result in the production process being altered.

3.5 Scenario 5—Reducing the Workforce

In the fifth scenario, the workforce was reduced from a total of thirteen workers down to ten, the results of which are shown in Table 6. The mechanism that made this possible was to instruct the machine operators to perform visual inspection tasks as well.

The scenario has shown extensive improvements in the economic pillar, as the lower Labor Cost has a direct impact on the profitability of the product. Whilst the model outputs indicate that the reduced head count did not alter the yield of the global process, this was only within the virtual time length of the simulation run. Observing the model directly during operation showed that the set-up would only allow for a few weeks of production with full yield until the buffer levels between machines deplete, at which point, production would slow down significantly due to a slower availability of product.

Table 6 Scorecard for reduced workforce

			Variation
Environmental performance			
1. Resource Utilization	(1) Energy utilization per unit	0.04442 kWh	−0.05 %
2. Waste	(2) Solid waste generated per unit	4.38667 g	−3.25 %
Economic performance			
3. Quality	(3) Scrap cost per unit	0.0308 €	−2.23 %
	(4) Reject rate	15.09 %	−4.02 %
4. Cost	(5) Overhead cost	0.03987 €	−21.39 %
	(6) Inventory cost	10234.78 €	−6.35 %
	(7) Unit cost	0.52699 €	−2.14 %
	(8) Labour cost	0.03454 €	−23.89 %
5. Delivery	(9) Cycle time	4.33735 s	0.00 %
Social performance			
6. Employee	(10) Daily kms walked	4.206 km	110.88 %

With regard to societal sustainability, the model only gave information about the increased fatigue experienced by the workers. Other implications may be possible. The societal impact of reducing the workforce could be immeasurable as motivation dips lower, whilst also reducing the employability of the process. This is all valuable insight on the sustainability of the process which could be used when considering the business and the production aspects. A more advanced simulation model, with better focus on societal metrics could provide even more guidance with regard to societal sustainability, which is currently not visible with this simulation study.

4 Conclusions

A simulation model which allows for the testing of different scenarios, relevant to the case study itself, was achieved. By asking IPD questions, the model gives predictive outputs related to the pillars of sustainability, therefore aiding decision-making with consideration towards the five components of Sustainable Integrated Product Development. This study has shown that simulation modelling with Tecnomatix can provide valuable insight on the behaviour of systems when subjected to changes, and can therefore be used as a tool to answer questions related to SIPD.

Whilst showing that simulation is a valuable tool for Sustainable Integrated Product Development, this study is not exhaustive in the use of applicable metrics, indicating that the above exercise can be extended to other metrics, specifically in the use of environmental metrics. Environmental implications and considerations can easily be added to the virtual model in the form of attribute data. The same cannot be said for societal considerations. With the current tools, software simulation is still rather inadequate for measuring the societal sustainability of a manufacturing line, and therefore requires more development for its effectiveness in achieving a tool for Sustainable Integrated Product Development with a complete Quintuple Bottom Line focus.

The exercise provided predictive information on the changes in behaviour a system would undergo when subjected to different inputs. The changes across the different metrics may have opposing consequences. This indicates that different metrics may require different weightings in order to choose between proposed changes. Investigation about the methodology for weighting different metrics would be of further value to the use of simulation for SIPD decision-making.

Throughout the duration of this study, limitations were encountered. These include insufficient data regarding societal factors specific to the plant and difficulty in measuring certain parameters and metrics. A more thorough investigation to deal with these issues could provide further insight and knowledge towards a better use of software simulation for sustainable integrated product development.

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Life Cycle Assessment and Life Cycle Costing as Supporting Tools for EVs Lightweight Design

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Abstract This study is concerned with the lifecycle impact and cost of lightweight design for Electric Vehicles (EVs). The applicability of novel materials, bio-composite and fiber reinforced thermoset matrix primarily, and related innovative manufacturing technologies, is evaluated for some relevant modules of vehicle. The study is part of the ENLIGHT European project that aims to advance highly innovative lightweight materials and technologies for application in structural vehicle parts of future volume produced (EVs) along four axes: performance, manufacturability, cost and lifecycle footprint. The preliminary results showed that, for the specific studies, material production and manufacturing represent the most critical life-cycle phases from environmental and economic point of view respectively. The trade-off between impacts of production and use phase needs to be faced by means of detailed analysis when EVs lightweight solutions are proposed.

Keywords Lightweight design · Composite · Electric vehicles · Manufacturing · Life cycle assessment · Life cycle costing

1 Introduction

Among the various economic sectors, that of transportation has a large contribution to several environmental burdens, greenhouse gas (GHG) emissions and resource exploitation among others [1]. Transports are responsible of 14 % of global direct GHG emissions [1] which are encountered throughout the whole life cycle of vehicle (i.e. materials production, manufacturing, use and end-of-life). In the

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automotive field, Electric Vehicles (EVs) are seen as a suitable path to reducing dependency on oil, decreasing CO_2 emissions and allowing zero-local-emissions in city centers [2]. Weight reduction is a crucial aspect for EVs and, thus, improvements from the application of novel materials (fiber reinforced thermoset, thermoplastic, bio-based or hybrid materials) are expected, especially for the use phase although the potential benefit has to be evaluated during the whole life cycle of the EVs, in a comprehensive way and by avoiding burdens shifting problems [3, 4]. This implies the necessity to identify potential sustainability issues in the design phase, and, consequently, to apply dedicated methods/tools able to characterize and compare the impacts of different solutions, thus, supporting the designer in the identification of the most sustainable (from an environmental, economic and also social perspective) [4, 5]. While the advantages by the adoption of light materials brings benefit to the end-user during the use phase of the vehicle, the costs are moved to the manufacturing phase, as well as the end-of-life of the vehicle, and become a burden for the OEM, who is responsible for both these phases [6]. The redistribution of costs along the lifecycle of the components as well as the need for measuring the benefits over the initial investments for the development of composites has motivated stakeholders of the automotive industry to adopt estimation models for assessing the life cycle costs and environmental performance of lightweight materials in automobile applications during the whole lifecycle of the parts, in order to provide the full picture [6]. In this context, the Life Cycle Assessment (LCA) [7] and Life Cycle Costing (LCC) [5, 6] approaches support carmakers in assessing and reducing the total energy consumed as well as the lifetime GHG emissions of vehicles taking also into account the economic aspect related to the adoption of different design solutions and choice of materials. Many Life Cycle Assessment (LCA) studies have already been proposed by several companies in the transport sector [10–12], and particularly in the automotive field, as demonstrated by the high numbers of technical reports of car manufacturers [13, 14] and scientific publications [15–20]. In many cases environmental evaluations are even integrated to LCC analysis [2, 6, 21–24]. These studies demonstrate that the application of new light weighting materials at component level is more studied in the case of internal combustion engine (ICE) vehicle than in the electric ones. However it is evident that the same light weighting solution could not guarantee the same benefit in the two cases. In the case of electric vehicle the risk of burden shifting between life cycle phases and impact categories is higher than in ICE vehicle.

In the present paper, LCA and LCC are used to assess environmental and economic performances of innovative solutions for EVs components with the aim to support the decision making for materials and processes since the early design phase. In this sense the important contribution of this work rely on two elements: (i) the integration of environmental and economic point of view; (ii) detailed level of analysis which could guarantee to have a more precise evaluation of achievable benefit from a life cycle perspective.

2 The ENLIGHT Project

The ENLIGHT project is interconnected with past and running initiative on lightweight technologies (particularly ALIVE project [25]). The main objectives of ENLIGHT deal with innovative lightweight and low embodied CO_2 materials and manufacturing technologies enabling significant weight reduction for five module of an EV: Front module, Cockpit and Firewall, Central floor section, Sub-frame and suspension, and Doors/enclosures (Fig. 1). This means a weight reduction ranging between 40–58 % with respect to benchmark EV.

The design of each module has been finalized considering the novel materials and associated manufacturing technologies developed within the project. Different approaches to light weighting have to be followed according to the part of the car at hand, as each area needs to comply with different functional specifications. For example, today the cockpit and the firewall are completely separated systems with large weight saving potential if integrated into one module. Thus, ENLIGHT intends to advance state of the art by pursuing a new module design where innovative materials are combined with integration of functionalities (cockpit, instrument panel and firewall system).

3 Methodological Approach

Life Cycle Assessment and Life Cycle Costing have been carried out within each module design workflow as well as materials development and technologies phases, representing powerful instruments to compare different

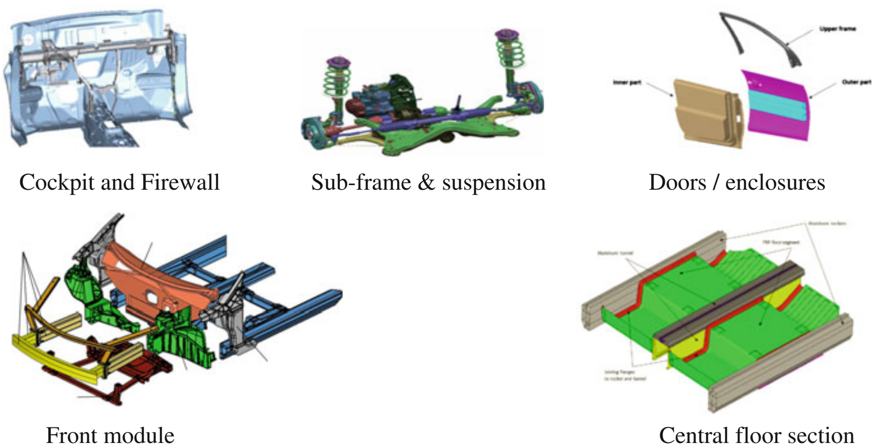

Fig. 1 References for ENLIGHT modules

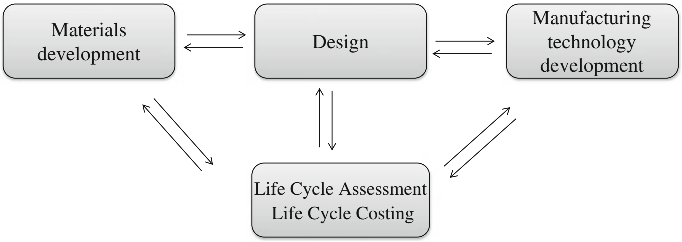

Fig. 2 LCA and LCC role in the modules design phase

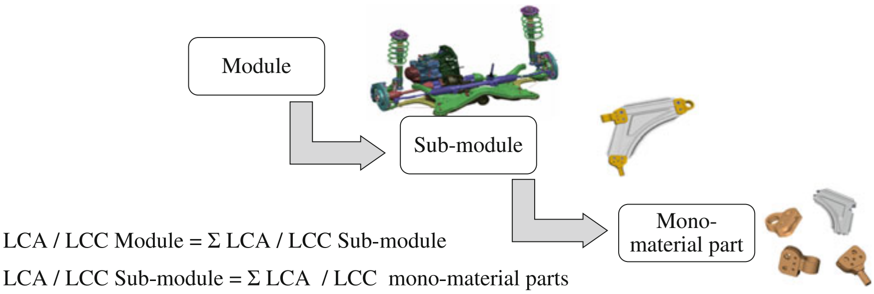

Fig. 3 Breakdown approach for LCA and LCC

design/materials/technologies alternatives and to orient towards sustainable solutions. These methods are even applied for validating the finalized modules design (Fig. 2).

A breakdown approach was applied for both LCA and LCC in order to guarantee a good level of detail and enhance comparison of results. For each module the data collection is done by considering the different sub-modules and mono-material parts involved; as a consequence LCA and LCC outcomes for each module are obtained as the sum of LCA and LCC of several mono-material parts (Fig. 3).

3.1 Life Cycle Assessment

Life Cycle Assessment is an environmental accounting methodology, which enables the quantification and evaluation of environmental effects produced during the whole life cycle of a product. According to the ISO 14040-44 standards, LCA is an iterative process encompassing four steps: (i) Definition of the goal and scope of the study; (ii) Life Cycle Inventory (LCI); (iii) Life Cycle Impact Assessment (LCIA); (iv) Interpretation of results.

Within the ENLIGHT project the overall scope of the LCA is to support decision-making about the choice of materials and manufacturing technologies during the design phase, then to address environmental aspects regarding the entire life cycle of the innovative EV components developed.

An adequate Functional Unit for the purposes of the ENLIGHT LCA study has been defined, describing the specific function of the module at hand provided during a life-distance of 150,000 km.

In this paper the presented outcomes are referred to system boundaries including raw materials extraction, manufacturing and consumed energy production (use phase). End-of-Life treatments generally represent a lower contribution in term of emissions so were excluded for a first screening [26, 27]. However, end-of-life phase will be further detailed in term of module recyclability and recoverability in the next steps of the project. Transports, battery production and maintenance were excluded since are assumed invariable.

Within the project, the data gathering (materials, energy, emissions, waste) was performed by means of specific questionnaires concerning novel materials production, innovative manufacturing technologies and design solutions to collect information about materials quantity, energy consumption and scraps rate. Secondary data from GaBi database were used for PA410, epoxy resin, carbon fiber, glass fiber and energy production eco-profile. In the modeling of use phase the environmental impact due to each module mass during the entire life-time has been estimated by correlating the variation in car weight between the scenarios of presence and absence of the module to the corresponding variation in energy consumption. The mass-induced energy consumption over the New European Driving Cycle has been estimated around 0.69 kWh/100 kg * 100 km [25]. Therefore, the energy consumption attributed to the component was calculated through the following formula.

$$energy_{component} = \frac{energy_{MI} \times mass_{component}/100 \times use_{km}/100}{eff_{battery} \times eff_{charge}} \quad (1)$$

where

- $energy_{M1}$ is the mass-induced energy consumption [kWh/100 kg*100 km];
- $mass_{component}$ is the mass of the component [kg];
- use_{km} is the life-distance [km];
- $eff_{battery}$ is the battery efficiency assumed 85 % [25];
- $eff_{charger}$ is the charger efficiency assumed 95 % [25].

In the use phase modeling the downsizing effect is assumed negligible and the energy consumption for heating/AC system is excluded as can be considered constant. The European average electricity mix has been assumed.

The Life Cycle Impact Assessment is performed by means of the mid-score method CML 2001. The following impact categories have been selected: Acidification Potential (AP); Eutrophication Potential (EP); Global Warming Potential (GWP 100 years); Photochemical Ozone Creation Potential (POCP). Even Primary Energy Demand (MJ) is calculated.

3.2 Life Cycle Costing Model

Unlike the LCA, there are currently no ISO standards available which are valid for LCC [23]; therefore in order to assess the lifecycle cost of the ENLIGHT modules, a tailored LCC cost model has been developed and implemented referring to the same functional unit of LCA. The costs estimated by the model consider the manufacturing phase—including cost of main machines and tools, manufacturing energy consumption, cost of consumables, labor—the use phase—which includes cost of energy to transfer the part throughout its lifecycle—and ending with the end-of-life of the modules—including transportation, and recycling/incineration costs. Figure 4 illustrates the input needed, assumptions, and output of the model for each of the three phases. However, end-of-life is excluded for the moment in order to have results comparable with LCA. Taking into consideration the input mentioned in Fig. 4, the relationship describing the calculation of the lifecycle cost of each module is the following.

$$Cost_{Part} = C_{Material} + C_{Machines} + C_{Tooling} + C_{Labour} + C_{Energy} + C_{Use} + C_{EoL} \quad (2)$$

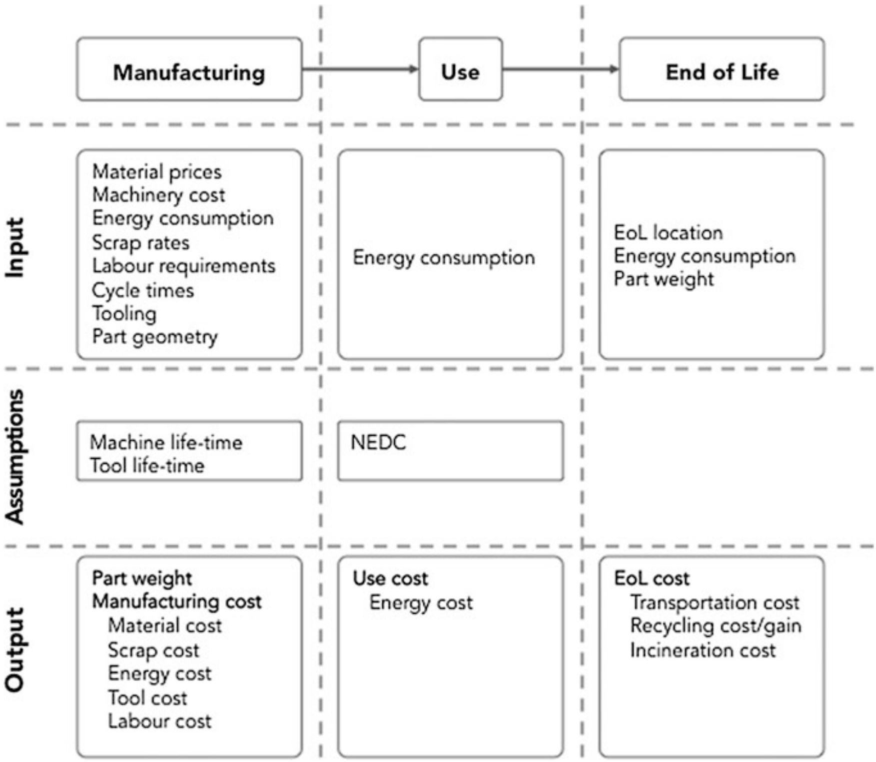

Fig. 4 Input, assumptions and output for each phase of the LCC model

where

- $C_{Material} = Weight_{Part} \times (Content_{Fibre} \times Price_{Fibre} + (1 - Content_{Fibre}) \times Price_{Matrix})$
- $C_{Machines} = \sum_{i=1}^{n_i} \frac{Cost_{Machine_i}}{Write-OffTime_{Machine_i}} \times \frac{1}{ProductionCapacity_{Yearly}}$
- $C_{Tooling} = \sum_{i=1}^{n_i} \frac{Cost_{Tool_i}}{Cycles_{Tool_i}} \times \frac{1}{ProductionCapacity_{Yearly}}$
- $C_{Labour} = Rate_{Labour} \times \frac{CycleTime_{Process}}{3600}$
- $C_{Energy} = Weight_{Part} \times EnergyConsumption_{Process} \times Rate_{Energy}$
- $C_{Use} = Energy\widetilde{Consumption} \times \frac{LifeDistance}{100} \times \frac{Rate_{Energy/Fuel}}{1000} \times Weight_{Part}$
- $C_{EoL} = Transportation_{Part} + Recycling/Incineration_{Part}$

The data used for the model were collected from literature and the industry. Particularly, for the manufacturing phase and material properties data were retrieved from research partners within the consortium. Manufacturing information (cost of raw material, cycle times, main machines involved, employee requirements, cost of machines and consumables, etc.) were collected by means of interviews with industrial organizations (OEMs, automotive suppliers) within, and outside the consortium, as well as literature (GRANTA Edupack, publications); price of raw materials is considered variable, and depends on total order quantity. For the use phase, energy consumption per mass (kWh/kg km) was calculated according to the NEDC as described in Sect. 3.1, and the cost of energy was taken as the EU average. The labor and energy rates (both for the manufacturing and use phase) are taken as the European average [28].

4 Results

Particularly, LCA and LCC analysis regard all the five automotive modules, but, due to the limited space available, only preliminary results for suspension and doors will be presented.

4.1 Components, Materials and Technologies Description

The ENLIGHT door concept was developed according to function integration principle and to utilize new materials and processes to deliver the door functions of "manage impact energy" and "satisfy aesthetics" with lower weight than the benchmark doors. The main parts are made of composites (Table 1) allowing some 25 % weight reduction. The composite materials used are TeXtreme® laminate based on carbon fiber reinforced Unidirectional (UD) tapes or glass fiber with DSM EcoPaxx® PA410 as matrix. The PA410 selection was guided by four factors: (i) thermo-mechanical performance to fulfill the primary design function;

Table 1 Materials and processes used for the each sub-module of the suspension arm an door

Door		Suspension arm	
Parts	Materials	Parts	Materials
Outer door skin	PA410/CF	Loose bearing	Alu
Intrusion beam	PA410/GF	Lower fixed bearing	Alu
Waist rail reinf	PA410/CF	Upper fixed bearing	Alu
Rear glass guide	Alu	Laminate	Epoxy/CF
Front glass guide	Alu		
Latch reinf	Steel		
Hinge intrusion beam	Alu		
Door inner	PA410/CF		
Total weight	7 kg[a]	Total weight	1,7 kg[a]

[a]expected mass

(ii) compliance with regulations and standards, such as REACH; (iii) lightweight material solution to gain travel distance per battery charge (i.e. low density, high stiffness); (iv) low embedded carbon footprint of both processes and materials. In fact PA410 from DSM is currently 70 % bio-based and can be reinforced with either continuous glass or carbon fiber. The choice for glass or carbon fibre depends on balance between stiffness, strength, impact and weight demands, and follows requirements and design optimizations. The TeXtreme® is an innovative reinforcement which has proved to combine the good impact behaviour and mechanical strength of a conventional woven reinforcement with the stiffness of a UD reinforcement. Moreover, within ENLIGHT project, the weaving process was adapted to be able to weave impregnated thermoplastic tapes, thus allowing cost reduction and more suitable manufacturing process for a high production rate. The laminate parts are manufactured with a hot stamping process, while the intrusion beam is made using an innovative continuous fiber placement process developed by Airborne®. This is a process to manufacture square profiles or beam elements in a fully automated continuous process, by melt-fusing UD tapes. These beams can be then processed to make more complicated structures. Advantages are the design freedom concerning fibre orientation as well as the capability of mass production.

Concerning suspension module the ENLIGHT project deals with suspension arm design. In this case two different concepts were developed; hereafter, the concept presenting functional integration is shown. It is a CFRP suspension arm with aluminum inserts and integrated piezo ceramics to improve the NVP properties (Table 1). As industrial manufacturing concept a fast RTM-process is foreseen. Specific simulations were carried out on these module solutions. For the door module a dynamic crash test were set with reference to some targets (i.e. intrusion levels); whereas in the case of suspension arm static and dynamic Finite Element (FE) model was set up to evaluate failure load.

4.2 LCA Results

The preliminary outcomes from the first iteration of LCA analysis of the innovative design solutions took into account the materials production and the use phases as the ones immediately affected by the application of multi-materials innovative solution. In the following graphs the contribution analysis of impact respectively for the suspension arm concept and door module by life cycle phases is reported. It can be noticed that the material production phase contributes to the majority of the impact categories for more than 60 % meaning that the benefits achieved by a weight reduction are otherwise combined with a not negligible impacts due to raw materials extraction and processing.

In particular CF reinforced composite is the main responsible; in fact, despite the lower impact of the bio-based matrix, the carbon fiber production has high CO_2 and energy intensive production (Fig. 5).

A sensitivity analysis concerning the energy mix showed that an increase between 2 and 9 % is registered for the GWP value if specific country-mix of Italy and Germany are assumed for the use phase. While a 22 % decrease is found when the country-mix of France is applied. However the material production phase still remains the most important stage to be focused on in order to achieve considerable advantages from an environmental point of view. Within the ENLIGHT project the reference solution has been identified by the designers for each module. Specific life cycle-based assessment of that solutions are not available, for that reason a simplified analysis of them is being carried out in order to evaluate environmental changes if compared to the innovative solutions. Outcomes form a first impact assessment iteration are shown in Fig. 6. Overall it can be seen that the eco-indicator values (referred to the selected CML 2001 impact categories) are slightly in favour of the innovative solution, thus suggesting a whole improvement. An increase of impact during the production phase (materials and manufacturing) can be noticed for both components; however, more precise evaluations about the real benefit could be obtained only once the modules concepts will be finalized.

4.3 LCC Results

The lifecycle analysis for the suspension arm as well as the door was performed for the different phases of the part's lifetime. The analysis is based on the part geometry, pre-selected materials, and manufacturing processes for high volume production of some 100,000 parts per year. Figure 7 illustrates the lifecycle cost phase for each of the mono-material part for the suspension arm and door. It can be clearly seen from the figures that the manufacturing and material costs for the composite parts are significantly higher than the metal parts, while their use cost is

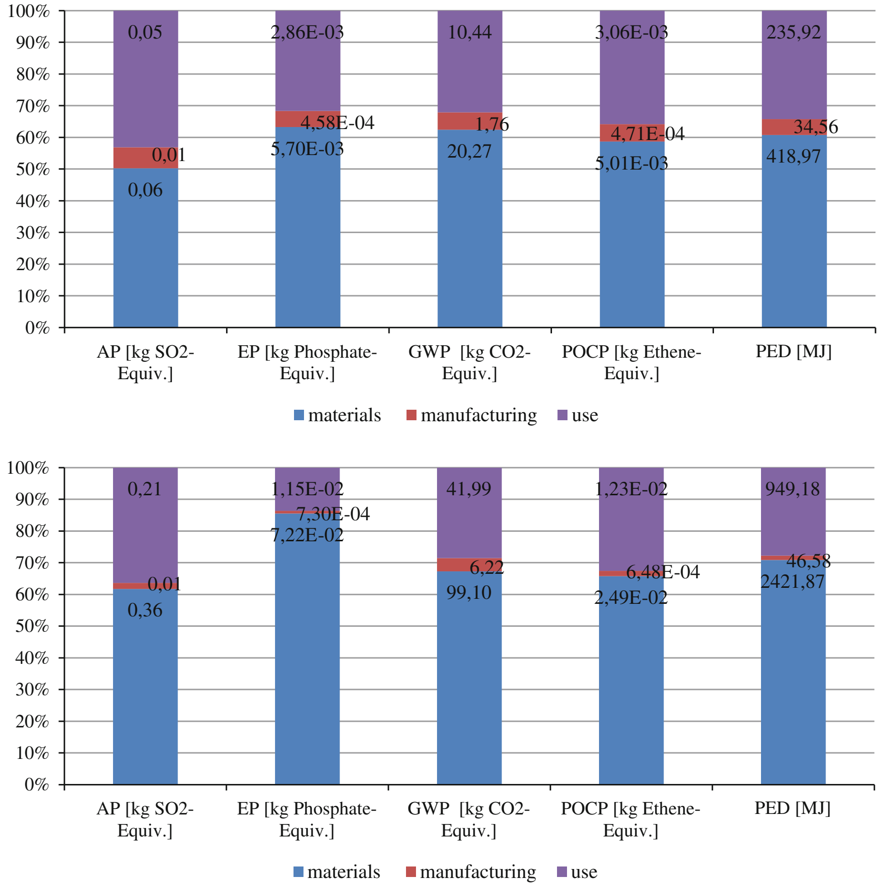

Fig. 5 Life cycle impact assessment breakdown per life cycle stages for the suspension arm (*upper*) and door module (*lower*)

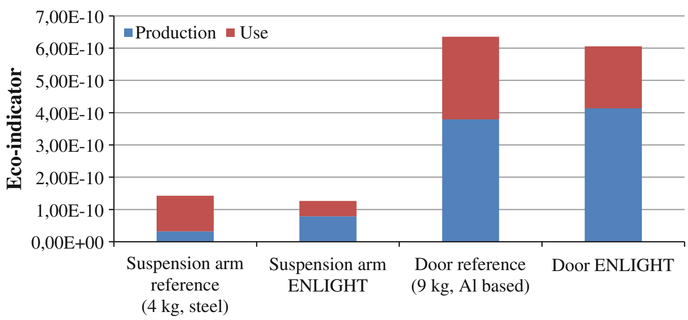

Fig. 6 Comparison between innovative and reference solutions: eco-indicator preliminary results (according to CML 2001 method)

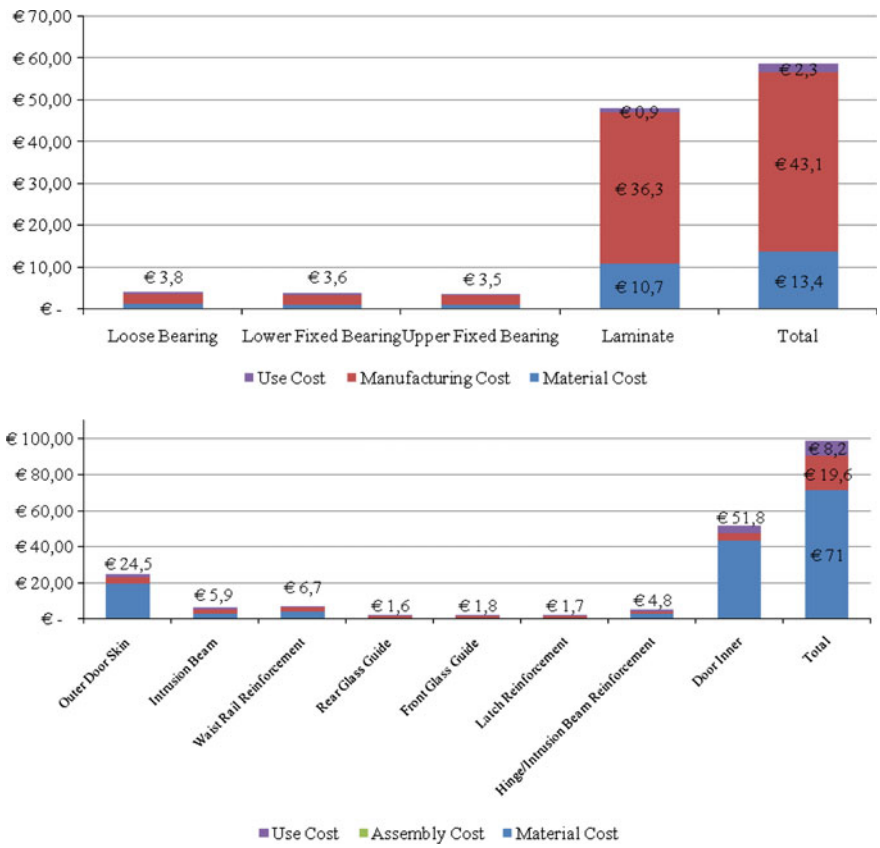

Fig. 7 Lifecycle cost breakdown and cost per kg, per mono-material part for the suspension arm (*upper*) and door module (*lower*)

relatively low, considering the volume they occupy in each of the modules. The manufacturing cost is particularly relevant for the suspension arm module where the total cost per kilogram is the double (32€) of the door module (15€).

A fluctuation of energy cost of ±15 % has an impact on the final module cost of some 1–1.5 %, depending on the manufacturing processes used, and their energy consumption, while the same fluctuation on raw material cost has an impact of ~11 % on the final part. As it would be expected, the fluctuation of materials prices is the parameter which would have the biggest impact on the final module cost, as they consist a major part of the final module cost.

5 Discussion and Conclusions

The paper looks into the lifecycle impact and cost of lightweight composite automotive parts. The case study performs analyses on selected EVs modules developed within the ENLIGHT collaborative project. The lifecycle assessment and cost analysis was performed for each mono-material sub-module and for the different phases of its lifecycle. The preliminary results show that the effects of light weighting are not always evident, and can highly vary according to the design, materials, and manufacturing processes; moreover, the results are strongly sensitive to small mass variations due to the low weight of the studied components. Additionally, where cost benefits might be positive, environmental impact might be negative and vice versa, showing the need for a balanced approach when developing parts, taking into account all aspects, and looking at the various impacts. A preliminary comparison between the innovative and reference solutions are even shown for the environmental part; overall the use of plastic composite materials is responsible of a burden increase in the production phase which is counter balance by the use phase reduction. Thus a whole improvement can be observed according to the selected indicators. The use of new materials and manufacturing technologies would definitely influence the dismantlability of the component which consequently influence the recyclability/recoverability of the whole vehicle. In this sense specific scenarios for each component are under evaluation since the current available guidelines are referred to the entire vehicle. These results could give useful insights and will provide important information even for the final design setting.

Overall, the use of LCA and LCC analyses during the initial development stages would aid in steering the material and manufacturing processes selection into a direction that would allow mitigating negative impacts, and optimising costs. Finally, the detailed analyses on the final part would help in providing a more detailed breakdown of the impact and costs of the parts throughout their lifecycle, even by comparing it to the reference solution.

Light weighting in the future EVs, without reducing performance and safety, is a key aspect since additional weight translates into either reduced driving range or in heavier and more expensive batteries.

However, since the use phase contribution (i.e. consumed energy production) in the EVs is generally low the results stress that a careful analysis needs to be done concerning material processing whose environmental and cost burdens could nullify the weight reduction purpose. In fact, contrary to ICE vehicles, the EVs present a more delicate balance between potential improvements in the use phase and impacts due to materials production.

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The Characteristic Objects Method: A New Intelligent Decision Support Tool for Sustainable Manufacturing

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Abstract This paper presents a new multi-criteria decision-making method, which is called the Characteristic Objects method, in the field of sustainable manufacturing. This approach is an alternative for AHP, TOPSIS, ELECTRE or PROMETHEE methods. The paper presents the possibility of using the COMET method for sustainable manufacturing. For this purpose, a brief review of the literature is shown. Then the COMET method is presented in detail. At the end of the paper, a simple problem is solved by using the COMET method.

Keywords Fuzzy set theory · Characteristic objects method · AHP · ELECTRE · Sustainable manufacturing · TOPSIS · MCDA

1 Introduction

Multi-criteria decision support methods are widely used in sustainable manufacturing problems [1–14]. In this area, the most commonly used criteria are economic, technical, environmental and social criteria [6, 15, 16]. These measures typically include opposing, and often conflicting interests. A good example would be to evaluate the economic and environmental assessment, which usually have opposite goals. Therefore, there is a need to identify expert models for sustainable manufacturing.

In the paper is presented a brief review of literatures in terms of the used methods and the research issues in the field of sustainable manufacturing. Subsequently, the paper presents a new approach to assisting decision, which is the COMET method [17–19]. This is the method which hasn't got many of the dis-

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advantages identified in the multi-criteria decision analysis methods [20–23] and, above all, is resistant to the phenomenon of rank reversal. Rank reversal is a reversal of the rankings when adding or removing an alternative or alternatives from the collection of the considered objects [19, 24]. For example, if we have a ranking of three alternatives A, B, and C (e.g. $A > B > C$), then we have the rank reversal after adding a new alternative D if the order of the alternatives A, B, and C is changed (e.g. $C > B > A > D$). It means that we have two different rankings by using the same method. This problem is solved in the COMET method by using the characteristic objects. As a result, we get a fuzzy model, which returns rankings with the unchanging order of alternatives. The paper also included a simple example intended to better illustrate the operation of the COMET method.

2 Literature Review

This section presents selected research papers related to multi-criteria decision-making support systems in sustainable manufacturing. These works are presented in terms of the method and subject of the research problem. Papers are presented in the outline in Table 1. This shows a great variety of problems that are solved by using methods of multi-criteria decision analysis, and at the same time presents the problem of selecting an appropriate method. A multitude of methods and their modification leads to the next problem, which method to use. This article presents

Table 1 Illustrative applications and methods of multi-criteria decision support for sustainable manufacturing

Application area	Method	Reference
Optimization challenges at different levels	AHP	[5]
Priority evaluation of product metrics	AHP	[3]
Supplier assessment	AHP	[2]
Evaluating sustainable manufacturing practices	AHP	[4]
Developing sustainable manufacturing initiatives	AHP	[7]
Strategy selection for sustainable manufacturing	AHP + VIKOR	[10]
Structural decisions of sustainable strategy	fuzzy ANP	[8]
Supplier selection in blood bags manufacturing	TOPSIS	[12]
Olive farms sustainability	TOPSIS	[9]
Prioritizing drivers for green manufacturing	TOPSIS	[6]
Prioritizing sustainable electricity technologies	TOPSIS	[11]
Sustainable concept selection	PROMETHEE	[13]
Assess sustainable energy options	PROMETHEE	[1]
Integrating sustainability assessment	PROMETHEE	[14]
Sustainable energy futures	ELECTRE	[25]
Assessment of green supply chain	ELECTRE	[26]

the COMET method, which eliminates the problem of rank reversal, and in addition to the existing research, shows greater accuracy than other methods of multi-criteria decision support. It has been shown in numerical experiments in [17–19].

In the literature, the most frequently considered problems are the tasks related mainly to: prioritizing [3, 6, 11], choice of supplier [2, 12], selection strategies (scenario) [1, 5, 8, 13] or performance rating (utility) [4, 7, 9, 14]. In order to solve them, the authors use of classical methods or their fuzzy extension. These are mainly methods such as: Analytic Hierarchy Process (AHP) [2–5, 7, 10], fuzzy ANP (fANP) [8], Technique for Order of Preference by Similarity is Ideal Solution (TOPSIS) [6, 9, 11, 12], Elimination and Choice Expressing Reality (ELECTRE) [25, 26], and Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) [1, 13, 14]. All these problems can be solved by using COMET method, which is a potential alternative for methods presented in the Table 1.

3 Fuzzy Set Theory: Preliminaries

The development of fuzzy set theory was initiated by Lofti Zadeh, who presented the idea and first conception of fuzzy sets in his seminal paper "Fuzzy Sets" [27]. Today, fuzzy set theory is a very important approach to control and model in various scientific fields. Modelling using Fuzzy sets has proven to be an effective way for formulating multi-criteria decision problems [28–30]. The basic definitions of notions and concepts of Fuzzy Set Theory are presented as following definitions [17–19]:

Definition 1 Fuzzy set and membership function.

The characteristic function μ_A of a crisp set $A \subseteq X$ assigns a value either 0 or 1 to each member in X inasmuch as crisp sets only allow full membership $(\mu_A(x) = 1)$ or non-membership at all $(\mu_A(x) = 0)$. This function can be generalized to a function $\mu_{\tilde{A}}$ so that the value assigned to the element of the universal set X falls within a specified range, i.e., $\mu_{\tilde{A}} : X \to [0, 1]$. The assigned value indicates the membership grade of the element in the set A. The function $\mu_{\tilde{A}}$ is called the membership function and the set $\widetilde{A} = \{(x, \mu_{\tilde{A}}(x))\}$, where $x \in X$, defined by $\mu_{\tilde{A}}(x)$ for each $x \in X$ is called a fuzzy set [31–34].

Definition 2 Triangular fuzzy number (TFN).

A fuzzy set $\widetilde{A}$, defined on the universal set of real numbers $\Re$, is said to be a triangular fuzzy number $\widetilde{A}(a, m, b)$ if its membership function has the following form (1) [33]:

$$\mu_{\underset{A}{\sim}}(x,a,m,b) = \begin{cases} 0 & x \leqslant a \\ \frac{x-a}{m-a} & a \leqslant x \leqslant m \\ 1 & x = m \\ \frac{b-x}{b-m} & m \leqslant x \leqslant b \\ 0 & x \geqslant b \end{cases} \tag{1}$$

and the following characteristics (2, 3):

$$x_1, x_2 \in [a,b] \wedge x_2 > x_1 \Rightarrow \mu_{\underset{A}{\sim}}(x_2) > \mu_{\underset{A}{\sim}}(x_1) \tag{2}$$

$$x_1, x_2 \in [b,c] \wedge x_2 > x_1 \Rightarrow \mu_{\underset{A}{\sim}}(x_2) < \mu_{\underset{A}{\sim}}(x_1) \tag{3}$$

An example of triangular fuzzy number $\widetilde{A}(a,m,b)$ is presented in Fig. 1.

Definition 3 The support of a TFN $\widetilde{A}$.

This is the crisp subset of the set $\widetilde{A}$ whose all elements have non-zero membership values in the set $\widetilde{A}$ (4):

$$S(\widetilde{A}) = \{x : \mu_{\underset{A}{\sim}}(x) > 0\} = [a,b] \tag{4}$$

Definition 4 The core of a TFN $\widetilde{A}$.

This is the singleton (one-element fuzzy set) with the membership value equal to one (5):

$$C(\widetilde{A}) = \{x : \mu_{\underset{A}{\sim}}(x) = 1\} = m \tag{5}$$

Definition 5 The fuzzy rule.

The single fuzzy rule can be based on tautology Modus Ponens [33, 34]. The reasoning process uses logical connectives *IF–THEN*, *OR* and *AND*.

Definition 6 The rule base.

The rule base consists of logical rules determining causal relationships existing in the system between fuzzy sets of its inputs and output [34, 35].

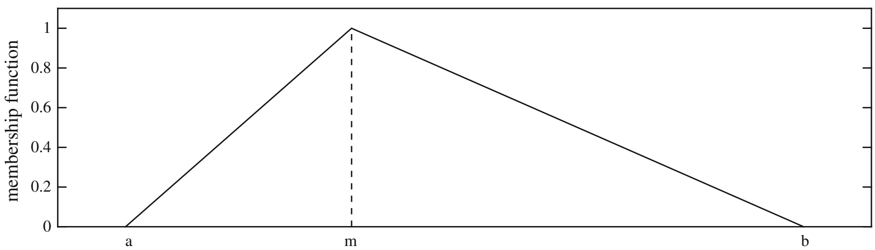

Fig. 1 An example of a triangular fuzzy number with supprt [a, b] and core m

Definition 7 T-norm operator: product.

The t-norm operator is a function T modeling the intersection operation AND of two or more fuzzy numbers, e.g. $\widetilde{A}$ and $\widetilde{B}$. In this paper, only product is used as a t-norm operator [33–35] (6):

$$\mu_{\widetilde{A}}(x)\, AND\, \mu_{\widetilde{B}}(y) = \mu_{\widetilde{A}}(x) \cdot \mu_{\widetilde{B}}(y) \tag{6}$$

4 The Characteristic Objects Method

The COMET method is a very simple approach, which is completely new method in the field of sustainable manufacturing problems. The basic concept of the COMET method was proposed by prof. Piegat [22, 23]. In the previous works, the accuracy of COMET method was verified. The proposed approach is more efficient than MCDM methods (e.g. AHP or TOPSIS methods). The formal notation of the COMET method is presented in the five following steps [17–19, 36].

Step 1. Define the space of the problem—an expert determines the dimensionality of the problem by selecting a number r of criteria, $C_1, C_2, \ldots, C_r$. Subsequently, the set of fuzzy numbers for each criterion C_i is selected, i.e., $\widetilde{C}_{i1}, \widetilde{C}_{i2}, \ldots, \widetilde{C}_{ic_i}$. In this way, the following result is obtained (7):

$$\begin{array}{l} C_1 = \{\widetilde{C}_{11}, \widetilde{C}_{12}, \ldots, \widetilde{C}_{1c_1}\} \\ C_2 = \{\widetilde{C}_{21}, \widetilde{C}_{22}, \ldots, \widetilde{C}_{2c_1}\} \\ \ldots \\ C_r = \{\widetilde{C}_{r1}, \widetilde{C}_{r2}, \ldots, \widetilde{C}_{rc_r}\} \end{array} \tag{7}$$

where $c_1, c_2, \ldots, c_r$ are numbers of the fuzzy numbers for all criteria.

Step 2. Generate the characteristic objects—The characteristic objects (CO) are obtained by using the Cartesian Product of fuzzy numbers cores for each criteria as follows (8):

$$CO = C(C_1) \times C(C_2) \times \ldots \times C(C_r) \tag{8}$$

As the result of this, the ordered set of all CO is obtained (9):

$$\begin{array}{l} CO_1 = C(\widetilde{C}_{11}), C(\widetilde{C}_{21}), \ldots, C(\widetilde{C}_{r1}) \\ CO_2 = C(\widetilde{C}_{11}), C(\widetilde{C}_{21}), \ldots, C(\widetilde{C}_{r2}) \\ \ldots \\ CO_t = C(\widetilde{C}_{1c_1}), C(\widetilde{C}_{2c_2}), \ldots, C(\widetilde{C}_{rc_r}) \end{array} \tag{9}$$

where t is a number of CO (10):

$$t = \prod_{i=1}^{r} c_i \tag{10}$$

Step 3. Rank the characteristic objects—the expert determines the Matrix of Expert Judgment (*MEJ*). It is a result of pairwise comparison of the characteristic objects by the knowledge of an expert. The *MEJ* structure is as follows (11):

$$MEJ = \begin{pmatrix} \alpha_{11} & \alpha_{12} & \ldots & \alpha_{1t} \\ \alpha_{21} & \alpha_{22} & \ldots & \alpha_{2t} \\ \ldots & \ldots & \ldots & \ldots \\ \alpha_{t1} & \alpha_{t2} & \ldots & \alpha_{tt} \end{pmatrix} \tag{11}$$

where α_{ij} is the result of comparing CO_i and CO_j by the expert. The more preferred characteristic object gets one point and the second object gets zero point. If the preferences are balanced, both objects get a half point. It depends solely on the knowledge of the expert and can be presented as (12):

$$\alpha_{ij} = \begin{cases} 0.0, & f_{exp}(CO_i) < f_{exp}(CO_j) \\ 0.5, & f_{exp}(CO_i) = f_{exp}(CO_j) \\ 1.0, & f_{exp}(CO_i) > f_{exp}(CO_j) \end{cases} \tag{12}$$

where f_{exp} is an expert mental judgment function.
Afterwards, the vertical vector of the summed Judgments (*SJ*) is obtained as follows (13):

$$SJ_i = \sum_{j=1}^{t} \alpha_{ij} \tag{13}$$

The last step assigns to each characteristic object the approximate value of preference. As a result, the vertical vector P is obtained, where i-th row contains the approximate value of preference for CO_i. We use here the principle of an insufficient reason. This algorithm is presented as a fragment of a Matlab code:

```
k = length(unique(SJ));
P = zeros(t,1);
for i = 1:k
    ind = find(SJ == max(SJ));
    P(ind) = (k - i) / (k - 1);
    SJ(ind) = 0;
end
```

In line 1, the number k is obtained as a number of unique value of the vector *SJ*. In line 2, the vertical vector P of zeros is created (with the identical size as a vector *SJ*). In line 4, the index with the maximum value from the vector *SJ* is obtained. This index is used to assign the value of preference to an adequate position in a vector *P* (based on the principle of indifference of Laplacea). In line 6, the maximum value of the vector *SJ* is reset.

Step 4. The rule base—each characteristic object and value of preference is converted to a fuzzy rule as follows, a general form (14) and a detailed form (15):

$$IF\ CO_i\ THEN\ P_i \tag{14}$$

$$IF\ C(\widetilde{C}_{1i})\ AND\ C(\widetilde{C}_{2i})\ AND \ldots THEN\ P_i \tag{15}$$

In this way, the complete fuzzy rule base is obtained.

Step 5. Inference and final ranking—each alternative is a set of crisp numbers corresponding with criteria $C_1, C_2, \ldots, C_r$. It can be presented as follows (16):

$$A_i = \{a_{1i}, a_{2i}, \ldots, a_{ri}\} \tag{16}$$

Each alternative activates the specified number of fuzzy rules, where for each the fulfillment degree of the conjunctive complex premise is determined. The preference of alternative is computed as the sum of the product of all activated rules, as their fulfillment degrees, and their values of the preference. It works as the Mamdani model. The final ranking of alternatives is obtained by sorting the preference of alternatives. Therefore, the assessment of each alternative depends on characteristic objects only, which are unchanging. It guarantees, that the COMET method is free of the rank reversal phenomenon.

5 Experimental Study

The purpose of this section is to identify the simple fuzzy model of assessment of sustainable manufacturing strategies. For this aim, the presented problem is described by using three criteria ($r = 3$). Thus, considered strategies will be assessed in respect to impact on: environment (C_1), social criterion (C_2), and economic criterion (C_3). The values of these criteria will be normalized in the range from 0 to 1, where 0 means the worst option and 1 means the best option in respect to each criterion. Figure 1 presents two linguistic values as triangular fuzzy numbers (Fig. 2).

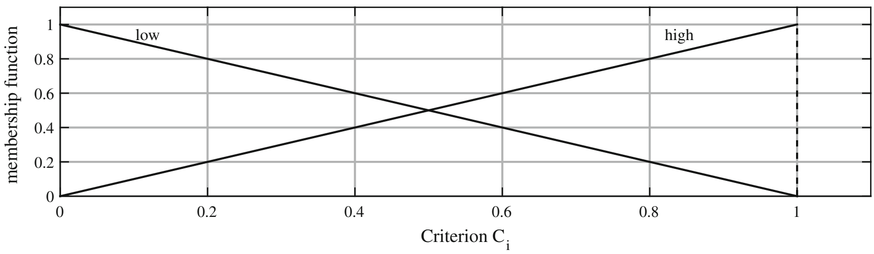

Fig. 2 The membership functions for the low level (about 0) and high level (about 1) for the i-th criterion

Table 2 List of 8 characteristc objects CO_i

CO_i	C_1	C_2	C_3
CO_1	Low	Low	Low
CO_2	Low	Low	High
CO_3	Low	High	Low
CO_4	Low	High	High
CO_5	High	Low	Low
CO_6	High	Low	High
CO_7	High	High	Low
CO_8	High	High	High

In this way, eight characteristic objects are obtained, which are presented in Table 2. Then, the expert makes pairwise comparisons in accordance with the formula (12) thus forming a matrix *MEJ*. Sometimes, it can mean a lot of questions for the expert, but as a result we get a continuous model. When we add or remove even one alternative, then we have to use the AHP procedure from the beginning. In the COMET method, we have the model, which allows assessing a number of alternatives. Subsequently, knowledge of the *MEJ* matrix is aggregated to the vector *SJ*. For the considered problem, the *SJ* vector and matrix *MEJ* is presented as (17–19). Creating a MEJ matrix requires only 28 pairwise comparisons, which allows to identify the decision maker's preferences and build a fuzzy model. Each set of alternatives can be evaluated automatically because the fuzzy rule base (20) is a perfect substitute for our expert. In reality, this decision model is calculated exactly in the same way as the Mamdani model.

$$MEJ = \begin{pmatrix} 0.5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0.5 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0.5 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 0.5 & 1 & 0 & 0 & 0 \\ 1 & 1 & 1 & 0 & 0.5 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 1 & 0.5 & 0 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 0.5 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0.5 \end{pmatrix} \tag{17}$$

$$SJ = \begin{pmatrix} 0.5 & 1.5 & 2.5 & 4.5 & 3.5 & 5.5 & 6.5 & 7.5 \end{pmatrix}^T \quad (18)$$

$$P = \begin{pmatrix} 0 & \frac{1}{7} & \frac{2}{7} & \frac{4}{7} & \frac{3}{7} & \frac{5}{7} & \frac{6}{7} & 1 \end{pmatrix}^T \quad (19)$$

$$\begin{array}{llllllllll} R_1: & IF & C_1 \sim low & AND & C_2 \sim low & AND & C_3 \sim low & THEN & 0 \\ R_2: & IF & C_1 \sim low & AND & C_2 \sim low & AND & C_3 \sim high & THEN & \frac{1}{7} \\ R_3: & IF & C_1 \sim low & AND & C_2 \sim high & AND & C_3 \sim low & THEN & \frac{2}{7} \\ R_4: & IF & C_1 \sim low & AND & C_2 \sim high & AND & C_3 \sim high & THEN & \frac{4}{7} \\ R_5: & IF & C_1 \sim high & AND & C_2 \sim low & AND & C_3 \sim low & THEN & \frac{3}{7} \\ R_6: & IF & C_1 \sim high & AND & C_2 \sim low & AND & C_3 \sim high & THEN & \frac{5}{7} \\ R_7: & IF & C_1 \sim high & AND & C_2 \sim high & AND & C_3 \sim low & THEN & \frac{6}{7} \\ R_8: & IF & C_1 \sim high & AND & C_2 \sim high & AND & C_3 \sim high & THEN & 1 \end{array} \quad (20)$$

6 Conclusion

The COMET method is completely free of the rank reversal phenomenon. It allows to use this method in the issues related to sustainable manufacturing problems. This approach is significantly more resistant to human error than the one used in the AHP Saaty rating scale, because an expert determines, which characteristic object from a pair is more preferred. There is no need information about the strength of this relationship as the AHP case. Therefore, the human error is minimized. This further simplifies the process of decision support. Applying the COMET provides reproducible results and their persistence in relation to a particular expert in the space of a problem. This method, in many cases, allows a more accurate assessment of alternatives than other MCDM methods.

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Green Supplier Selection Framework Based on Multi-Criteria Decision-Analysis Approach

Jarosław Wątróbski and Wojciech Sałabun

Abstract The aim of this article is to present the framework for dynamic suppliers' evaluation and selection. The proposed framework defines input information together with a methodological background required for decision support processes. Authors suggest using the multi-criteria decision-analysis (MCDA) methodology to propose a dynamic approach. Therefore, the fuzzy TOPSIS method has been selected as a method that provides the ability to aggregate numerical and linguistic data, which are obtained from various inputs. After discussions on a framework outline, an empirical study is given. The presented problem concerns the selection of a supplier for the company producing cable bundles. Finally, a ranking for 25 vendors (for 12 periods) is obtained as a result, which facilitates the diversification of supplies for the discussed company.

Keywords Fuzzy set theory · Supplier selection · Framework · Supply chain management (SCM) · TOPSIS · Multi-criteria decision-analysis (MCDA)

1 Introduction

One of the most important elements of the effective management of business organizations is a correct evaluation and selection of market suppliers. These issues are fundamental for running core business companies but also for providing services in the auxiliary areas. The selection and monitoring of suppliers is a widely discussed problem, where supplier plays a key role [1]. Current market conditions are based on, inter alia, the need for long business relationships with suppliers [2] or minimize the risk of purchasing [3]. The evaluation of suppliers, and more broadly the whole chain of SCM and green SCM, are therefore important factors affecting

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the competitive position of the company [4]. This becomes particularly important for manufacturing companies where materials represent, on average, sixty percent of the cost of a finished product and fifty percent of the complaints are due to faulty material purchasing [4]. The complexity and multidimensional nature of sustainable supply chains and green logistics management affects the level of risk for all participants throughout the supply chain and its management [5], e.g., negligence in coordinating deliveries adversely affect the service and cause long delays [6].

From the business point of view, an important issue is not just a one-off evaluation but also the ongoing monitoring of the service quality and the quality of products/semi-executed and delivered by key business partners—suppliers of the company. Therefore, the research problem taken in our paper is how to develop a framework for a dynamic evaluation of suppliers? Natural implications are further questions which analytical methods should be used in this aim? and how the reference model should be built for supplier evaluation that would allow its repeated use by decision-makers?

This kind of the assessment takes into account a very important but often overlooked aspect in the work of volatility during the final assessment cooperator, which seems to be very important in an era of dynamic changes in the market. The proposed approach assumes the cyclic (repeated) nature of such an assessment, which in practice translates not only into more reliable monitoring of the service provider but also allows forecasting and tracking any trends such as changes. The dynamic evaluation of suppliers identifies those among them who have the greatest potential corresponding to the requirements of companies and are a direct way to reduce costs, improve competitiveness and the product quality [7]. The periodic nature of the evaluation can simultaneously deploy modern and effective management technologies such as just-in-time approach in practice minimizes actively involved in the basic capital and translates into a strong competitive position. The rejection of a dynamic process of supplier evaluation may lead to distort the whole key supply chain organization [2].

From a methodological point of view the aim of the article is to draw up guidelines for using the chosen MCDA methods in the process of cyclical evaluation. Moreover, it requires the necessity of preparing a reference model of criteria set for the problem of the green supplier selection. The work is presented as follows: after the literature review and problem statement, the conceptual framework of a dynamic evaluation of suppliers is presented. In the next stage, the proposed framework is used in an empirical study for dynamic evaluation of vendors. Finally, conclusions are presented.

2 Literature Review

The supplier selection problem is presented in a number of studies by the virtue of the topicality of this issue [8, 9]. In this kind of problems, a decision-maker chooses the most preferred vendor from a set of available suppliers taking into consideration different points of view (also taking into account a series of often contradictory criteria). Evaluation of suppliers is carried out using a number of analytical methods [10, 11]. Among them, multi-criteria methods play a very important role [12]. In the last time, the MCDA methods are more often selected. Table 1 presents a comparison of selected examples of used MCDA methods in SCM and green SCM problems. In the presented papers, authors take successful attempts to use several different multi-criteria decision-analysis methods for the construction of evaluation models of a key supplier of SCM. In these papers, main differences are an evaluation category, a method used, a type of criteria and structuring of the problem. However, all these examples present a one-off selection of suppliers. Moreover, the approaches are different in the structure and the form of individual sets of assessment criteria. It means that evaluation is made once for a long time period. It may cause that we will use information from an outdated ranking. Therefore, a dynamic approach to evaluate suppliers is needed, and particularly relevant in an era of dynamic changes in the market. Additionally, constructing a framework containing a reference set of assessment criteria of the green supplier allows the decision-maker to construct separate models in an individual and simplified manner taking into consideration their individual preference model.

Table 1 Comparison of examples of used MCDA methods in SCM problems

No.	Evaluation category	Method	Number of criteria/subcriteria	Type of criteria	Year	References
1	C, Q, S	ANP and TOPSIS	7	Mixed	2006	[17]
2	C, Q, S	fANP	7/24	Mixed, fuzzy	2013	[7]
3	Q, S	fTOPSIS	5	Qualitive, fuzzy	2006	[3]
4	C, Q, S	fAHP	5/19	Fuzzy, mixed	2007	[2]
5	C, Q, S	fAHP	7	Fuzzy, mixed	2011	[18]
6	C, Q, S	AHP	6/16/35	Mixed	2008	[19]
7	Q, S	fANP	11	Qualitive, fuzzy	2013	[1]
8	S	ANP and fTOPSIS	5	Qualitive, fuzzy	2011	[5]
9	C, Q, S	AHP	2/5/26	Mixed	2001	[20]
10	Q, S	ANP	3/9/33	Qualitive	2007	[4]
11	C, Q, S	ANP	4/20	Mixed	2013	[6]
12	C, Q, S	fAHP	4/11	Fuzzy, mixed	2015	[21]
13	C, Q, S	fTOPSIS	6/25	Fuzzy, mixed	2013	[22]
14	C, Q	SWOT, TOPSIS	4/8	Fuzzy, qualitive	2011	[10]
15	S	fDELPHI, fAHP	5/12	Qualitive, fuzzy	2015	[23]
16	C, Q, S	fCM, VIKOR, AHP, CFA	9/26	Fuzzy, mixed	2015	[24]

(continued)

Table 1 (continued)

No.	Evaluation category	Method	Number of criteria/subcriteria	Type of criteria	Year	References
17	C, Q, S	fAHP	12	Fuzzy, mixed	2013	[25]
18	C, Q, S	ANP, VIKOR	6/16	Mixed	2012	[26]
19	Q, S	fANP	5/16	Fuzzy, mixed	2011	[27]
20	C, Q, S	fVIKOR	5	Fuzzy, mixed	2011	[28]
21	C, Q, S	Agent-based model	7	Fuzzy, mixed	2015	[29]
22	S	MCDA	6	Mixed	2015	[11]
23	Q, S	AHP	4/12	Mixed	2012	[30]
24	C, Q, S	fANP	7	Fuzzy, mixed	2014	[31]
25	S	AHP, TOPSIS	8	Qualitive	2014	[32]
26	C, Q, S	fAD	11/60	Fuzzy, mixed	2015	[9]

Abbreviations C—cost, *Q*—quality, *S*—service and functionality, *f*—fuzzy, *AHP/ANP*—analytic hierarchy/network process, *TOPSIS*—technique for order of preference by similarity to ideal solution, *SWOT*—strengths, weaknesses, opportunities and threats, *AD*—axiomatic design

3 Proposed Framework

From a methodological point of view, this paper uses a dynamic approach to generate a periodic evaluation of suppliers using the fuzzy TOPSIS method. The complete procedure of fuzzy TOPSIS can be found in [3]. The general concept of the TOPSIS method assumes to create an evaluation matrix. Data in this matrix can be represented by fuzzy numbers. On the basis of that, we define the positive and negative ideal solution. The presented approach is based on the concept that the chosen alternative should have the shortest geometric distance from the positive ideal solution and the longest geometric distance from the negative ideal solution. The final assessment is obtained by calculating the relative closeness to the ideal condition.

Using the linguistic terms policymakers make weight evaluation criteria and their rankings. We assume that two data sources will be used, i.e., knowledge of experts and existing in any company the ERP (Enterprise Resource Planning) system. The data download from the ERP using, e.g., an SQL (Structured Query Language) query for the audited period takes place automatically. The system builds a model of knowledge supplemented with survey data, which is stored in the database. A historical data model is able to convey to decision-makers trends on the basis of which they make a selection of suppliers. A periodic automatic selection is performed using weights and ranking criteria supplemented for the first time when

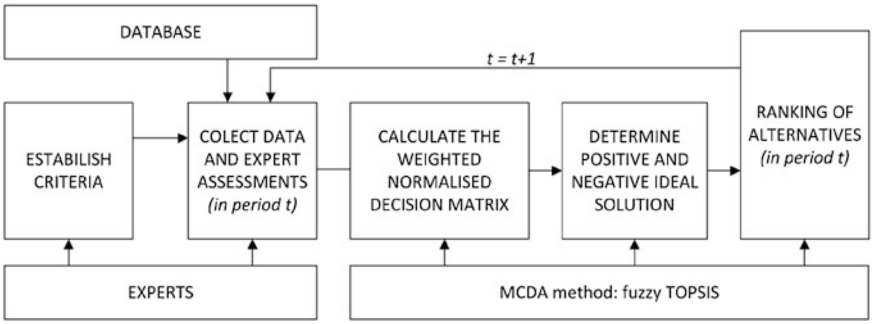

Fig. 1 Outline of framework for dynamic evaluation of suppliers

circumstances will not require them to change. The scheme to carry out the automatic ranking of suppliers is shown in Fig. 1.

At the beginning of the process, a committee of decision-makers, whose first task will be to identify the evaluation criteria, must be formed. It is a structuring phase. In the next step, the appropriate linguistic variables for the importance weight of the criteria and the linguistic ratings for alternatives with respect to criteria are chosen. In the literature, triangular and trapezoidal fuzzy numbers [13, 14] are most often chosen. As it has been pointed in this paper, each ranking is calculated by using Fuzzy TOPSIS. The fuzzy set theory is perfect to deal with problems in which a source of vagueness is involved. Thus, it has been utilized for incorporating imprecise data into the decision framework. A fuzzy set A can be defined mathematically by a membership function $\mu_A(x)$, which assigns each element x in the universe of discourse X to a real number in the interval [0,1]. For more details on this subject and calculating procedure, refer to [3, 15, 16]). The system aggregates the weight of criteria to get the aggregated fuzzy weight of each criterion [3, 13], and pool the decision makers' opinions to get the aggregated fuzzy rating of each alternative under each criterion. At this stage, the system collected the data and knowledge in a period t. On the basis of the gathering data, the fuzzy decision matrix is constructed. Subsequently, the matrix is normalized and then is taken into account weight of each criterion. The rest of steps are typical for the TOPSIS method. We obtained a fuzzy positive and negative ideal solution (fPIS and fNIS). Then, we calculated a distance of each alternative from fPIS and fNIS, respectively. Finally, the closeness coefficient of each alternative is calculated. According to the closeness coefficient, the ranking order of all alternatives (all suppliers) is determined (in a period t). The next evaluation will be made for a period $t + 1$. In a new time period, the system collected the data and expert knowledge in the period $t + 1$. If the length of time period is too short, we will obtain rare changes in the ranking. This means more frequent operations of the evaluation system. In that case the level of redundancy will be higher. On the other hand, if the length of the time period is too long, some changes in the ranking will be omitted. The selection of the time period is individual and depends on the specificity of a problem.

4 Empirical Study

In this empirical study, we consider the problem of evaluation suppliers for a cable bundles company. After preliminary screening, 25 suppliers remain for further evaluation ($A_1 - A_{25}$). For this problem, a committee of experts has been formed (DM_1, DM_2 and DM_3). Then, the set of criteria is presented in detailed form in Table 2. Subset of criteria refer to data retrieved from the ERP. The rest of criteria requires filling surveys by experts (by using linguistic ratings). For a time period t = 1, we use a fuzzy TOPSIS procedure and we get results for each alternative in the first iteration. The committee set a time interval for one month. Table 3 presents

Table 2 Set of criteria for suppliers' evaluation and selection

No.	Criteria	Description/subcriteria	Ref.
1	Cost	Product costs, total supply cost, price, financial cost, operating expenditure, after-sales costs, sunk/loss cost/customer dissatisfaction, suppliers production pauses	[2, 7, 8]
2	Product quality	Quality of the product, package, rejects rate, warranty	[2, 8]
3	Quality	Quality of service, quality system certificate of the supplier, quality assurance, conformance quality, quality image	[20, 28]
4	Delivery/Logistics	Conformance to quantity, choice of transportation, reliability of quality, delivery flexibility, serious delivery delay rate, warehouse management, IT management, confirmed fill rate, total order cycle time, system flexibility index, integration technologies level, increment in market share, research and development ratio, procurement	[21, 22, 24–26]
5	Financials of manufacturing and product	The last term profit, exporting status, profit/sale trends, finance stability, interest on payment purchasing, discount, debt ratio and current ratio, distributors in good financial positions, recapturing value, revenue from the sale of recyclables, profit margin, liquidity	[11, 19, 30]
6	Risk factors	Geographical location, political stability, economy, terrorism, distance, natural disasters, technology, delivery risk, risk management	[17, 31]
7	Service	Standard of service, the service capability, responsiveness (warranty, packaging capacity responsiveness), technological R&D support, information acquisition, punctuality, value added services to customers (assembly/reassembly, repackaging/re-labeling, remanufacturing)	[2, 10, 11, 17, 27]

(continued)

Table 2 (continued)

No.	Criteria	Description/subcriteria	Ref.
8	Profile	Customer base, performance history, production facility and capacity, facility location, the number of working years in this sector, references, communication capability, the number of personnel, education status of the personnel, machine capacity and capability, manufacturing technology, facilities manufacturing capacity, handling and packaging capability, appropriateness of the quantity and the packaging standards	[2, 7]
9	Green innovation	Green technology capabilities, green process/production planning, recycling product design, renewable product design, green R&D project, redesign of product	[1, 9]
10	Environment protection	Environment protection system certification, policies and plans	[9]
11	Environment management	Production of material ecologically efficient, eco-design requirements for energy using products, level of restriction of hazardous substance in the production process, compliance with the local regulations	[9]
12	Pollution control	Air emissions, waste water, pollution control capability, pollution reduction capability	[9]
13	Hazardous substance management	Management of hazardous substances in the production procedure, prevention of mixed material, process auditing, warehouse management, inventory of hazardous substance	[9]
14	Green image	Ratio of green customers to total customers, green customers market share, stakeholders relationship, green materials coding and recording	[11, 24]
15	Social responsibility	The interests and rights of employee, the interests and the right of shareholders, consumers, information disclosure, expose nonfinancial information, respect for the policy	[9, 11]
16	Green product	Recycle, green packaging, cost of component disposal, green certifications, green production, reuse, re-manufacture, disposal	[9,11]
17	Green materials	Materials used in the supplied components that reduce the impact on natural resources, ability to alter process and product for reducing the impact on natural resources	[9, 11, 24]

the complete set of results for 12 months and for all 25 suppliers. Sometimes, a supplier may not be available, e.g., the 7th supplier in a period t = 2 or the 14th supplier in periods t = 2, 3, 12. Through the use of the proposed framework, we can additionally check the dynamics of the assessment. This can be a helpful tool for

Table 3 Evaluation of all suppliers for 12 periods

A_i	Number of period *t*											
	1	2	3	4	5	6	7	8	9	10	11	12
1	0.42	0.46	0.47	0.46	0.49	0.43	0.38	0.45	0.47	0.49	0.44	0.48
2	0.42	0.44	0.46	0.46	0.50	0.45	0.44	0.46	0.49	0.49	0.45	0.50
3	0.45	0.48	0.53	0.50	0.54	0.48	0.44	0.46	0.51	0.56	0.48	0.53
4	0.39	0.41	0.45	0.46	0.45	0.42	0.43	0.44	0.46	0.47	0.49	0.46
5	0.47	0.49	0.55	0.55	0.55	0.52	0.48	0.48	0.54	0.58	0.49	0.55
6	0.44	0.47	0.51	0.50	0.52	0.48	0.48	0.48	0.51	0.53	0.49	0.52
7	0.36	**xxx**	0.37	0.39	0.40	0.38	0.39	0.43	0.46	0.44	0.40	0.46
8	0.42	0.44	0.45	0.50	0.51	0.43	0.43	0.46	0.51	0.51	0.47	0.50
9	0.44	0.45	0.54	0.54	0.53	0.46	0.45	0.53	0.56	0.56	0.52	0.54
10	0.44	0.45	0.47	0.50	0.50	0.47	0.47	0.51	0.49	0.52	0.50	0.50
11	0.44	0.41	0.49	0.48	0.50	0.42	0.42	0.46	0.49	0.49	0.45	0.49
12	0.46	0.47	0.49	0.52	0.54	0.48	0.48	0.50	0.54	0.55	0.49	0.52
13	0.35	0.36	0.35	0.39	0.40	0.40	0.34	0.36	0.40	0.45	0.40	0.44
14	0.42	**xxx**	**xxx**	0.48	0.51	0.47	0.50	0.46	0.50	0.52	0.47	**xxx**
15	**xxx**	0.35	**xxx**	0.38	**xxx**	**xxx**	**xxx**	**xxx**	0.44	0.44	0.37	0.42
16	0.46	0.46	0.48	0.49	0.52	0.47	0.43	0.46	0.48	0.50	0.48	0.52
17	0.42	0.43	0.45	0.47	0.52	0.47	0.41	0.48	0.51	0.51	0.48	0.52
18	0.45	0.46	**xxx**	0.50	0.49	0.47	0.40	0.43	0.53	0.47	0.46	0.48
19	0.43	0.41	0.43	0.45	0.48	0.44	0.44	0.35	0.45	0.42	0.42	**xxx**
20	0.39	0.36	**xxx**	0.41	0.38	0.39	0.32	0.38	0.44	0.39	0.34	0.38
21	0.46	0.45	0.45	0.44	0.48	0.44	0.39	0.46	0.46	0.47	0.44	0.48
22	0.36	0.34	0.39	0.38	0.38	0.35	0.31	0.39	0.42	0.44	0.38	0.42
23	0.45	0.48	0.52	0.47	0.55	0.46	0.48	0.50	0.52	0.51	0.49	0.54
24	0.43	**xxx**	0.47	0.44	0.49	0.43	0.46	0.43	0.49	0.48	0.42	0.49
25	0.40	0.45	0.53	0.47	0.54	0.41	0.48	0.45	0.55	**xxx**	0.49	0.50

xxx means not available supplier

prediction, which supplier may have a decrease or increase in an assessment in the next time period.

Figure 2 presents a pairwise comparison of variability evaluations of suppliers. In the case (a), we have an example where all the time supplier A_5 has a higher assessment than supplier A_3. For that kind of the pair, we can only analyze dynamics of assessment because the order is constant. We can calculate that supplier A_3 has a higher coefficient of variation than supplier A_5. This means that supplier A_5 was more stable. In the case (b), the order is changed throughout the analyzed time interval. Supplier A_9 has quite a high coefficient of variation but this is due to the improvement of its evaluation in the second half of the analyzed period. This pairwise comparison example shows why the dynamic evaluation is so important.

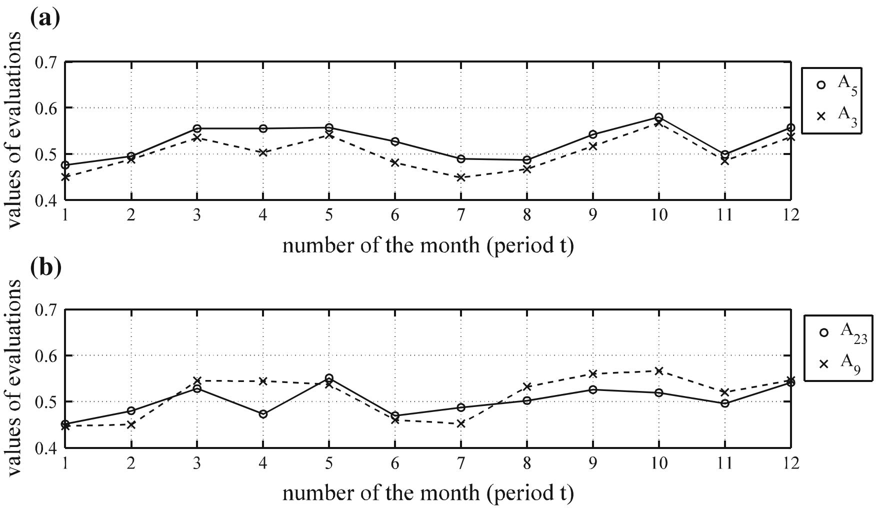

Fig. 2 Pairwise comparison of variability evaluations of suppliers, **a** two suppliers with changing evaluation and without changing the order, **b** two suppliers with changing evaluation and with changing the order

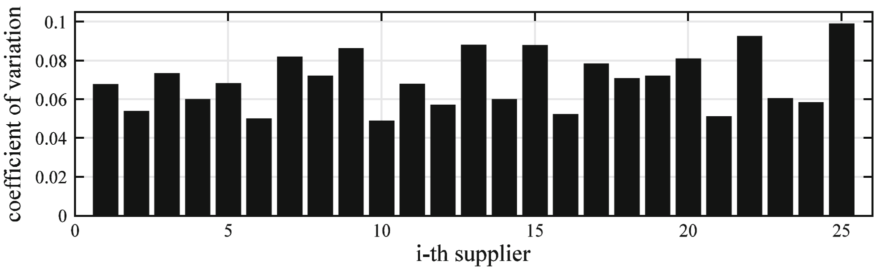

Fig. 3 Coefficient of variation for evaluation of each supplier (for 12 periods)

Figure 3 presents coefficients of variation for evaluation of each supplier (calculated as the ratio of standard deviation and average value). As we can see, the results were dynamic in the time. The highest coefficient of variation has supplier A_{25}, and the smallest has supplier A_5. This means that range of volatility is from 5 to 10 %. This is quite a lot especially that the maximum rating of 1 is the most idealized value, which almost never occurs. Additionally, these results allow classifying the suppliers into groups of risk, which depend on their coefficient of variation.

5 Conclusions

The paper presents a dynamic supplier selection framework, which is based on the multi-criteria decision-analysis methodology. The proposed approach is easy to use and the analyst must collect only ERP data and expert assessments in the next period. The fuzzy TOPSIS method copes very well with mixed data. It is especially important in the case when we use many imprecise, vague or linguistic data. The application of the proposed framework, in the short empirical study, showed that obtained assessments are not constant. Moreover, the volatility of ratings leads to a change in the ranking orders. Therefore, the cyclic approach in the evaluation of the suppliers is necessary.

The advantage of the approach proposed in the article is additional preparation of a reference set of criteria for the issue of the green supplier selection. The criteria in combination with the proposed framework make it possible to construct models taking into consideration decision-makers' present preference models as well as valid data. Future works should be concentrated on the question: what period of time is optimal to make a new assessment for the supplier selection problem.

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Part V
Invited Session 1: Design for Additive Manufacture

Application of Sustainable Design in Additive Manufacturing of an Unmanned Aerial Vehicle

Stefan Junk and Werner Schröder

Abstract A number of design rules must be adhered to in the development and manufacturing of unmanned aerial vehicles. In this, additive manufacturing, particularly in the implementation of requirements with respect to light-weight construction and sustainability, offers several advantages compared to conventional manufacturing methods. Therefore, this article will primarily introduce and compare current concepts for sustainable design using additive manufacturing. These will, above all, consist of the production of complete fuselages and wings by means of rapid prototyping or also rapid tooling. In addition, a new concept will be introduced in which a UAV using AM can be implemented through the combination of very light components and a preferably resource-saving manufacturing method. In this process, a three-dimensional spaceframe is used in combination with a covering in the construction of the wing. Hereby, the development process for sustainable design using additive manufacturing will be analyzed and the results will be explained by means of concrete case studies. In conclusion, the results of these case studies will be compared to the latest technology regarding wing span load.

Keywords Additive manufacturing · Design for manufacturing · Unmanned aerial vehicle · Sustainable design

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1 Introduction

The development and use of unmanned aerial vehicles (UAV) have greatly increased in significance over recent years. Many more uses are becoming applicable in civilian life along with their military uses. UAVs can be employed in the surveillance of technical facilities, in measuring or surveying large plots of land for agriculture or archeology as well as for the transport of goods [1].

Additive manufacturing procedures have also been increasingly used in the development and manufacturing of UAVs. In general, these have the advantage that the components can be delivered directly to manufacturing after their development in the CAD without additional working steps such as, e.g., the acquisition of tools or the programming of toolpaths, being necessary. In this manner, development times and costs can be drastically reduced [2]. The wide distribution and the rapidly growing market for additive manufacturing also make this technology interesting for the production of UAVs [3].

A further advantage of additive manufacturing is that ordinarily only materials for the actual building component are required. The only waste material that arises from this is the support structure which nevertheless consists of a very small percentage of the total construction volume. In contrast, the components are cut from a blank in conventional manufacturing whereby up to 50 % of the materials are lost as swarf. Even the use of energy in the manufacturing process is considerably lower in many cases in comparison to forming and cutting manufacturing [4].

In the course of this, the specifics of additive manufacturing must be considered. In addition, there are several publications available which examine construction of components that are ready to manufacture which are produced layer by layer [5]. Furthermore the generative manufacturing technologies they can be used both for the direct production of components and for the indirect production by means of tools. For example molds for the thermoforming of plastic foils can be manufactured using polymer plastics in Binder Jetting (BJ) technology [6].

Aside from this, additive manufacturing offers still further advantages which are of particular significance specifically for the manufacturing of UAVs. Most of all, diverse plastics can also be introduced alongside metals; these plastics enable a light construction. Also, this layer-by-layer manufacturing allows for the application of complex forms with free-form surfaces for the wings and tails. Furthermore, complex internal forms, such as stringers and also ribs in the fuselage, can also be easily implemented. Finally, additional geometric elements, such as, for example, supports for servomotors or openings for cables, can also be very simply integrating into the components of a UAV without any necessary additional working steps. Thus steps like milling, drilling or cutting can be dropped or reduced considerably.

2 The State of Technology

Due to the above-mentioned advantages, the use of additive manufacturing (AM) in the production of UAVs has intensified over the past several years (see Table 1). As a rule, plastics such as ABS, PLA and PA are used as the construction material. Both selective laser sintering (SLS) of plastic powders and fused deposition modeling (FDM) of plastic filaments are applied as manufacturing processes for the plastics. In this process, the additive manufacturing or rapid prototyping (RP) of individual parts frequently takes place first in combination with subsequent assemblage. Aside from this, AM is, however, also applied for the manufacturing of forms which serve as molds for rapid tooling (RT) in the manufacturing of components made of carbon fibers.

The first example of a UAV that was manufactured with the aid of SLS is “SULSA” which was developed at the University of Southampton in 2011 and based on the designs of planes from World War II [7]. For this, laser sintering was used as the construction process and polyamide as the material.

The University of Virginia introduced “Wendy” in 2012; it represented a reproduction of a tested design of a model construction. It was built with the aid of an FDM process which is more favorable than SLS owing to machine technology. ABS was used here as the material [8].

An attempt at a UAV which is likewise manufactured using FDM is the “Variable Airspeed Telescoping Additive Unmanned Air Vehicle” (VAST AUAV) by the Massachusetts Institute of Technology in 2013 [9]. MIT produced a composite construction consisting of carbon elements and elements from a 3D-printer. As a special feature, this UAV commands telescopically extendible wings in order to demonstrate various flying speeds.

The “Barcelona UAV,” introduced by the Polytechnic University of Catalonia in 2014, consists of a total of ca. 30 components made of PLA which was produced by means of an FDM process [10]. Moreover, the CAD-files with the components in

Table 1 Overview of UAVs using additive manufacturing

Name	SULSA	Wendy	VAST AUAV	Barcelona UAV	Fixed wing powered UAV
Year	2011	2012	2013	2014	2014
Organization	University of Southampton	University of Virginia	Massachusetts Institute of Technology	Universitat Politècnica de Catalunya	University of Sheffield, AMRC
Technology	SLS	FDM	FDM	FDM	FDM
Construction	RP	RP	RP, hybrid	RP	RP, RT, hybrid
Material	PA	ABS	ABS, carbon	PLA	ABS, carbon

STL-format and a simple construction manual were published on an open access database in the internet. Here, an extremely simple construction was accomplished in which the surface weight lies within the range of model airplanes made of closed-cell extruded polystyrene foam as in, for example, the "Easy Star II" model [11].

A UAV introduced in 2014, "Fixed wing powered UAV," likewise from the AMRC Design and Prototyping Group at University of Sheffield, has been chosen as an additional approach. In this, additive manufacturing was used to implement a hybrid construction [12]. The components were, in part, directly manufactured from the material ABS with the aid of FDM manufacturing. On the other hand, forming tools were also produced from ABS with the aid of FDM manufacturing and reworked which serve to manufacture components from carbon fibers. Thereby, both rapid prototyping and rapid tooling have been used in this example.

In all the previously introduced examples, all or at least a great number of the components were manufactured with additive manufacturing. FDM was predominantly used in these examples because the necessary facilities for this are significantly less expensive than facilities for laser sintering. In this process, components for UAVs would consist of the outer shell and a supporting structure on the inside. Relatively difficult constructions arise from this which, in most cases, weigh considerably more than UAVs made of foam which are of a comparable size.

3 Specifications for Sustainable Design for Additive Manufacturing

In this contribution, various development methods will be developed and the application thereof shown in order to reduce the material and energy consumption in the production of UAVs with the aid of AM. The specific course of working steps in the process chain of additive manufacturing must be followed. Initially, the design is made with the aid of CAD-programs. In this process, the individual components of the UAV are developed and drawn.

A great number of restrictions are to be observed in this working step. Needless to say, the aerodynamics as well as the stability of the components must first be ensured. Restraints in production technology also play a role in addition to this. In particular, the components must be producible with the aid of AM and subsequently also easy to assemble. It should be considered with regard to sustainability that whenever possible little material is used in the production and that the energy for the production and operation of the UAV is preferably low.

In the following processing step that is called "pre-processing", the support structures, in particular, are generated with the aid of software based on the STL data from the CAD in addition to the positioning in the installation space and the manufacturing of the layers. This is decisive for material consumption as it can significantly influence the creation and the positioning in the installment room.

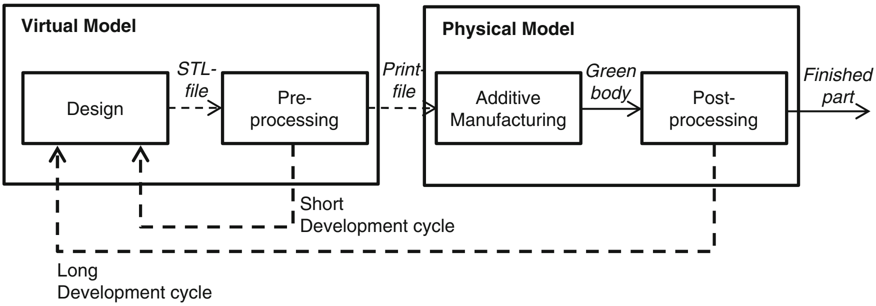

Fig. 1 Development cycles in design for additive manufacturing

In addition, the filling degree of the components can also be varied in FDM. Along with material consumption, this also influences the stability of the components. Initial optimizations can be made through critical observation of the results from pre-processing in order to improve the design. Material- and time-consuming misprints will be avoided in the subsequent process steps through this "short development cycle" (Fig. 1).

The actual building of the physical model takes place in the following process step after reading the print data. In this, electrical energy is required in particular for the movement of the axels and the heating of the extrusion jets to ca. 280 °C for the building material. Moreover, the construction chamber itself must also constantly be heated to a temperature of 70 °C. Above all, a short construction time is to be minded here with respect to sustainability since the consumption of energy can be reduced as a consequence.

Lastly, the post-processing of the half-completed 3D-model (green body) follows whereby the support structure is removed. In this process, no additional energy consumption accrues in the most favorable case because the supports can be mechanically, e.g. by breaking or cutting, removed. Support structures are unavoidable especially in complex geometrics. These are removed by a chemical process of an alkaline bath over a period of several hours. The smaller the support structure is, the less energy and raw materials are used in removing the supports. Errors and optimization measures, which are just now being discovered, can be taken into account in the manufacturing of following components in accordance with the "long development cycle" in design.

4 Case Study of Implementation of Sustainable Design in Additive Manufacturing

A UAV was developed and manufactured with the aid of the FDM process as a demonstration of the application of the two possible development cycles. This UAV is based on the principle of flying wings (see Fig. 2); that is to say, separate

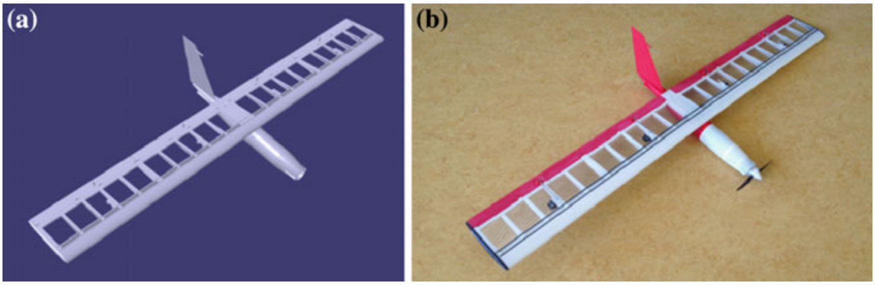

Fig. 2 "Spaceframe 3DP-UAV" developed from a 3D-printer at the University of Applied Sciences Offenburg: CAD model without covering (**a**) and UAV manufactured using fused deposition modeling FDM (**b**)

horizontal stabilizers are not used. The fuselage, the wing and the vertical stabilizer are all manufactured with the aid of AM. ABS is used as the construction material. The soluble support material is mechanically removed by breaking or can be chemically washed off with the aid of alkaline. The total length of this "Spaceframe 3DP-UAV" is roughly 610 mm plus the additional length of the folding propeller of 45 mm and wingspan is roughly 1600 mm.

Since the residues of the supporting material and of the alkaline bath must be disposed of as waste the volume of supporting material should be kept for reasons of the sustainability as low as possible. Moreover, it should be tried to make a mechanical removing of the supports possible in order to avoid the energy-intensive use of the alkaline bath. The fuselage and vertical stabilizer are manufactured as closed shells which retain sufficient stability through reinforcements. A construction principle is used in the wings which deviates from the model previously introduced in Table 1. In order to implement an especially simple construction method, only the front portion of the wing and the rudder will be transformed into closed shells; the largest portion of the wing consists of a frame that is covered with a covering. Hereby, the advantages of AM are used in order to manufacture this spaceframe structure as resource-saving as possible. Because the construction chamber for the FDM-printer only permits components up to ca. 200 mm high, the fuselage and the wings are divided into segments. In a subsequent assembly process, the segments are joined together by inserting or, respectively, bonding. Additional carbon rovings are brought into strengthen the wings. Finally, the necessary components for the motor, storage battery, cables and steering are also integrated into the UAV.

4.1 Example of Short Development Cycle

The short development cycle includes pre-processing. In the course of this, errors or possibilities for optimization which are discovered during pre-processing can be reported directly back to the design in order to improve the product.

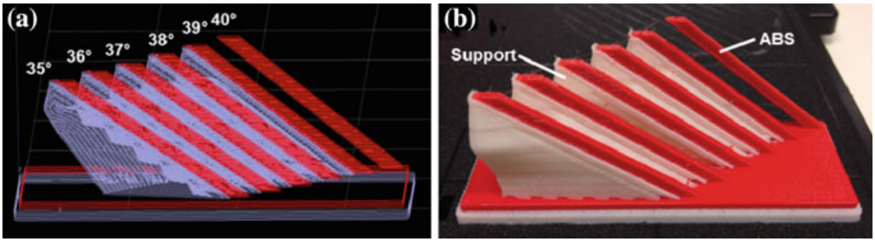

Fig. 3 Investigation of the necessity of support material at various angles in pre-processing (**a**) and as a test component (**b**)

Moreover, the short development cycle can be used to conduct basic investigations. Thus, for the construction of frame structures in the fuselage of the UAV, it was investigated at which angle from the base a support structure would not be necessary. This question is important in that additional support structures present an increased use of material. In addition, forgoing a support structure can avoid the tedious washing of the supports in an alkaline bath in post-processing or at least considerably reduce the manufacturing time. An investigation of the angle is represented in Fig. 3 whereby a support structure is no longer necessary. Thus, one can already recognize in the pre-processing that from an angle of 40° between the basis and the braces no support structures are created by the software. A sample part is additionally created for demonstration which explains this circumstance.

4.2 Example for a Long Development Cycle

A long development cycle is then necessary when errors are first detected in the manufacturing of the components. Thus, it can, for example, be determined that the support material can only be removed with difficulty by boring holes with very small circumferences. Therefore, in this case, the problem must be reacted to with a change in the construction of the bored holes.

Aside from this, many test models are only possible with real prototypes. Among these is a basic test such as, for example, the determination of the thickness of the material at different degrees of filling. There are also other concrete tests of components such as, for example, the bending strength of a wing or also ascertaining which adhesive is appropriate for binding the individual components.

The development of the "boundary segment" which represents a portion of the wing serves as an example here. The original construction (version 0) and the form optimized in several cycles (version 4) are pictured for comparison in Fig. 4. First the reduction of the material consumption was aim of the optimization. The production time and with that also the energy consumption of the FDM device and the recovery unit should be reduced.

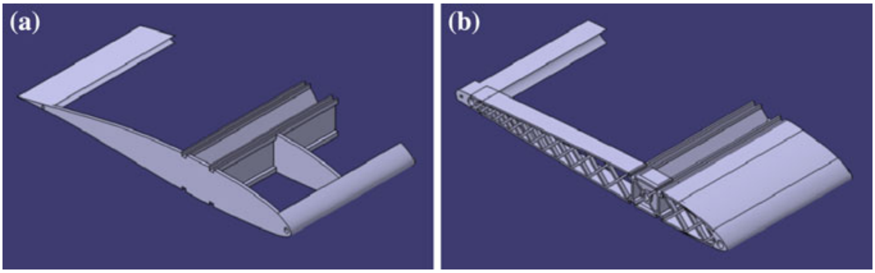

Fig. 4 Boundary segment in its original form (**a**, version 0) and after the completion of several development cycles (**b**, version 4)

Besides that, the optimization of the handling characteristics also was in focus. After the assembly it turned out that the heat-shrinking covering of the for-wing was too loose and inaccurate. Therefore the pre-wing was changed as a closed shell. For the reduction of the weight the rib was changed from a closed plate into a spaceframe construction.

With the optimization in several development cycles, the use of model and support material each can be reduced by ca. 9 %. Along with this, the construction time could also be reduced by ca. 31 % thereby optimizing the consumption of energy. From the aeronautical perspective, lightweight construction is particularly important as it shows that the mass per units of length in the individual steps in the development can likewise be reduced by ca. 7 %.

Several long development cycles were also carried out for the other elements of the wing. In order to improve the sustainability of the manufacturing process comparable savings to material and energy consumption could be reached for these elements too. The fuselage of the UAV, which consists of 4 several elements, was optimized in 3 cycles. The consumption of model material could be reduced by 54 %. The manufacturing time and within the energy consumption were reduced by 33 % in these development cycles. The design of the vertical stabilizer could be optimized so, that only mechanical cutting is needed and the post-processing in the alkaline bath becomes completely redundant.

5 Results and Discussion

A UAV that is manufactured with the aid of generative manufacturing can now be compared to other models. Wing loading which is a result of the ratio between the total mass of the UAV and the wing surface is qualified here as a parameter for comparison. However, the exact measurements of the geometry of the wings and the weight of the UAV cannot be sufficiently known in every case representing the latest technology. In order to simplify the comparison, the wing span load is employed in this case, hence the ratio between the total mass of the UAV and the

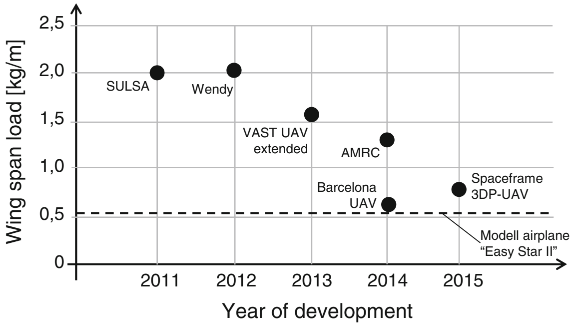

Fig. 5 Comparison of wing span load among various AM-manufactured UAVs and model airplanes of foam

length of the wings. Moreover, the wing span load of a typical model airplane, such as is commercially available, made of closed-cell extruded polystyrene foam, namely the "Easy Star II" model, is considered the standard of comparison [11].

The comparison shows that the wing span load of UAVs developed in the past few years has successively decreased. The figures from the year 2014 show that, for example, the Barcelona UAV features a wing span load which is very close to that of a model airplane. The UAV introduced in this article which features a closed shell on a frame construction rather than a wing cannot quite achieve this figure (Fig. 5).

In order to reduce the value of the wing span load, a reduction in the wall thicknesses in all parts of the UAV would be necessary. Unfortunately, the FDM-printer used in this case-study is not in the position to manufacture wall thicknesses smaller than 1 mm. Even when a low workpiece thickness is fixed in the design and thereby in CAD-data, a series of trials show that these low thicknesses are not implemented by the FDM-printer. In contrast to this, a different FDM-printer was used with Barcelona UAV; this 3D-printer is able to successfully manufacture much smaller wall thicknesses.

6 Conclusion and Outlook

The possibilities for the implementation of Unmanned Aerial Vehicles with additive manufacturing in the product development process have been examined in this contribution. Thereby, an observation of the latest technology shows that first models are already being created at various universities all over the world. These are predominantly manufactured with the FDM process. In the course of this, different processes, such as rapid prototyping and rapid tooling, are employed. Mixed or hybrid construction methods are often used in combination with reinforcements of carbon.

As a new approach a 3D-printed UAV using a spaceframe in combination with a bonded covering is presented. Diverse optimization loops are developed and applied in the product development process of this UAV. The first steps in design can be taken directly after pre-processing in short development cycles. In long development cycles, errors that are detected in manufacturing, post-processing or the subsequent assembly are reported back to the design for the purpose of elimination.

It could be shown in a case study in the example of the development of a wing for a UAV how both development processes can be practically applied. Hereby, basic investigations within the “short development cycle” are conducted in order to reduce the consumption of support material by means of pre-production construction. In addition, by the use of the “long development cycle” it could be shown that material consumption, the construction time and thereby also energy consumption could be reduced through constant optimization of the design in several steps.

A comparison of the wing span load currently depicts the tendency to reduce this load to the point of a range which until today has only been achieved by model airplanes made of foam. This contribution is restricted to the analysis of only one case study from the area of UAVs. Also only one type of material, namely ABS, is used within the experiments.

Therefore, it should be attempted in further developments of the UAV to continue to reduce the weight of UAVs and to improve the sustainability of the additive manufacturing process through the use of newer FDM-printers in connection with other materials. Moreover, improvements in aeronautical design, for example, the integration of brake flaps for landing, should also be implemented.

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Evaluating Innovative CAD Techniques in the Creation of Conformal Cellular Structures

Shwe Soe, Wassim Jabi and Peter Theobald

Abstract This paper focusses on demonstrating the effectiveness of our new code at producing curved, formerly planar structures that comprise complex internal architecture. This development is particularly significant as it will, ultimately, allow further exploitation of the design freedom offered by additive manufacturing (AM). This particular application focusses on head impact protection, and builds upon our previous work describing the promising mechanical performance that can be achieved by parametrically varying cellular shape, wall thicknesses and relative densities (Soe in Second international conference on sustainable design and manufacturing, 2015 [1]). In this current work, we explore the translation of these design concepts into application-based environments, focusing particularly on achieving structural contours whilst retaining mechanical performance. This paper aims to demonstrate our success at contouring previously-planar structures around hemispherical ('head') geometry, whilst retaining mechanical performance through the relative alignment of individual cellular structures. We first evaluate the capabilities of existing packages: (1) PTC Creo Parametric (mechanical CAD system) and, (2) Materialise 3-matic^{STL} (lightweight structures module); before demonstrating the effectiveness of our new script embedded within Autodesk 3D Studio Max. We conclude by comparing results from our script with equivalent data from the commercially-available software.

Keywords Additive manufacturing · Conformal geometries · Cellular structures · Design for manufacture · Personal protective equipment

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1 Introduction

1.1 Additive Manufacturing

Additive manufacturing (AM) offers great potential in seeking a sustainable manufacturing technique, with the ever-increasing availability of new engineering materials providing a genuine platform for producing functional products [2]. With such progress come new design challenges that otherwise limit AM from fully exploiting new areas of growth. This paper focusses specifically on the design challenges presented by attempting to geometrically conform low density ‘cellular structures’, whilst retaining their mechanical performance. This is relevant both generally in design for additive manufacture, and when designing specific consumer-related goods.

1.2 Design for Additive Manufacture: Energy Absorption Materials

Head injury protection technologies have remained broadly unchanged since the 1970s. Protective helmets generally comprise a thick *liner* and thin outer *shell*, with the former generally consisting of foam material. Typical thickness of foam liners are in the range of 20–30 mm though a thicker, more effective, liner is prohibited by user-preference/commercial constraints [3]. The energy absorption of a foam material is usually characterised by a series of compressive stress-strain curves. Under standard compression tests the material will show a small region of linear stiffness, followed by a long plateau region as the cell walls buckle. The plateau continues up to the densification strain, beyond which the structure compacts and the stress rises steeply. The amount of energy foam can absorb is measured by the area under the stress-strain curve to the point of densification strain. The energy per unit volume, the plateau stress and the initial stiffness values are useful comparison for an initial selection of a foam material [4].

Helmet test standards are regularly reviewed and updated to achieve better head protection, with the forthcoming standards creating opportunity for the commercial adoption of new manufacturing technologies [5–8]. Given that the efficiency of energy absorbing materials depends on both their structure and material, this paper investigates the combined functionalities of energy absorbent AM materials and unique cellular structures, specifically the conforming of these structures to curved geometries. This builds on our previous work, which involved the material characterisation of AM elastomeric materials that are suited to both laser sintering and fused deposition modelling processes [1, 2].

Previous works focusing on the design and manufacture of strong and lightweight structures are typically drawn from the aerospace community, with the potential relevance of functionally graded porous structures with tailored mechanical properties only recently recognized for biomedical applications [9–11]. To date, scant information exists relating structures and materials within an energy absorption environment. From a design perspective, traditional CAD packages are not particularly suited to creating complex cellular structures, though a new generation of CAD packages are now being investigated [12]. From an experimental perspective, cellular structures are usually created in a planar shape, both for ease of design and the extraction of performance data from mechanical testing; however, such an approach has very limited transferability to an end-use.

This study aims to investigative and resolve some of the design challenges faced when contouring previously-planar structures around a curved geometry (in this particular application, the human head) whilst, critically, maintaining mechanical performance through retaining the relative alignment of individual cellular structures. This challenge will be attempted independently using three different software packages.

2 Technical Evaluation of Existing Conformal Software

This section provides detail of our research into the functionality of two leading software packages. Ultimately, the limitations of these software will define the requirements of our new code.

2.1 Cellular Design in Creo Parametric

PTC Creo CAD system is parametric-based software that is primarily aimed at mechanical product design [13]. The process involved in creating a cellular structure starts with defining a set volume of a unit cell, using surfaces as an imaginary bounding box. A desired cell shape is constructed by the use of lines and curves in the predefined volume. A 3D cell skeleton (Fig. 1a) is formed by a network of curves, which are translated into solid beams (Fig. 1b) by assigning circle, square, triangle or hexagon cross-sectional parameters. The benefit of using a parametric model is that a variant cell size and shape can be obtained by altering the specific geometric parameters, whilst its relative density can be calculated from the actual volume of the CAD model to its overall cell volume. The linear patterning function conveniently achieves a multi-cell assembly, copying the original cell in three (x, y, z) directions. The overlapping distance (usually half beam thickness) between cells is precisely defined (Fig. 2a).

Whilst Fig. 2 describes the successful filling of a complex 2D shape with a cellular structure, it is unsuitable since the overall volume must be created larger than the target volume in all directions, to enable trimming through the use of an appropriate Boolean operation (Fig. 2b). As a result the orientation of cells will remain unchanged throughout the process, whilst the generation of unwanted cells

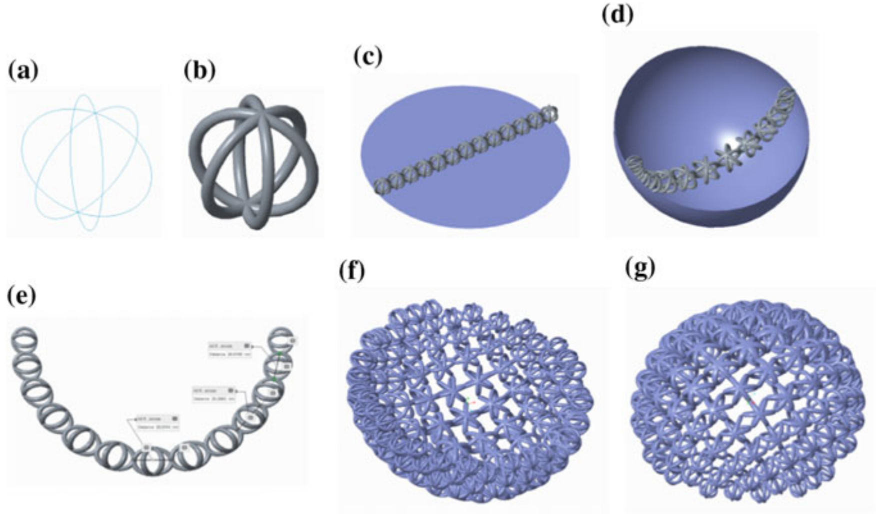

Fig. 1 Illustration of conformal cellular structure helmet inner-liner modelling steps in Creo software. **a** Wireframe cell unit, **b** TT-3 mm solid unit, **c** *Centre row* of cell units on flat surface before warping, **d** *Centre row* of cell units after warping along with surface, **e** *Front view* of conformal cellular units, **f** Completed conformal cellular structures (*Left*: inside and *Right*: outside views)

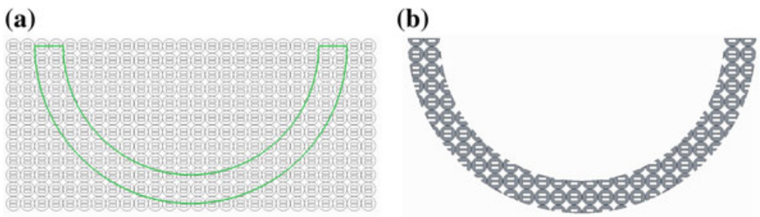

Fig. 2 Illustration of generated cell units, the target shape and trimmed cells. **a** Linear array of cells populated over the semi-sphere shape helmet inner-liner, **b** Remaining cell units after trimming

becomes computationally expensive and time consuming. Since the cell edges cannot be precisely trimmed, the structural rigidity of incomplete cells along the edge become weak. Furthermore, the failure to orientate each cell ‘normal’ to the outer surface will induce inferior mechanical performance relative to a planar structure. Our objective is to retain this mechanical performance—which is critical in some applications, by conforming the structural design such that each cell remains normal to the surface.

In Creo, one advanced tool employed to create a conformal shape is the use of its “warp” function. In this approach, a cell assembly is created using the above described method to populate cells in all three directions, though the overall height of a cell (or cells) can be adjusted and perfectly aligned to the shape thickness (20 mm in Fig. 1). Figure 1c shows the circular planar and a row of cellular TT structures before warping, with the corresponding warped structure depicted in Fig. 1d.

The benefit of using the warp function is that the cells are oriented normal to the top and bottom planes along each warping step. The degree of conformity depends on how close the overall geometry can be warped to the desired shape (Fig. 1e). Since exact matching between the warped shape and the final desired shape in this way is not always possible, the trimming method can be used as a final step. The symmetrical shape (of a helmet liner, in this instance) allows for the use of the warp function (Fig. 1f); however, a similar approach would be almost impossible where the desired shape is composed of asymmetrical geometries.

2.2 Cellular Design in Materialise 3-Matic

Materialise has developed 3-matic^{STL} software to manipulate and design features on an STL level via the "Design" module, which offers advanced meshing capabilities for FEA software applications via the "Remesh" module [14]. 3-matic's new "lightweight structures" module serves to generate complex cellular structures. Indeed, here we only evaluate one of the different techniques available for generating and filling cellular structures in a defined volume. In this approach the helmet inner liner created in Creo is firstly imported into 3-matic as STL format. Similarly, the cell structure in curve (wireframe) format prepared in Creo is imported into 3-matic using STEP format. It is important at this stage that the cell unit is aligned in a preferred direction with respect to the liner's inner surface. The next stage involves selecting a host surface on which the 2D conformal patterning operation will be performed. Since the liner has a constant thickness (20 mm), either the exterior or interior surface can be defined as host. Here the exterior surface is chosen with an assumption that the outside shape of the helmet is preferably fixed, for commercial reasons. As the 2D patterning function is initiated, the selected surface is mapped with a UV square pattern (black and white image; Fig. 3a). In this function the width and height of U and V patterns can be individually adjusted to obtain a rectangular shape, or fixed to achieve a square. Prior to performing 3D conformal patterning, a set of imported curves representing the cell need to be converted into a unit graph structure. In this function the previously created 2D pattern (liner inner surface) and a unit graph structure (TT cell structure) are selected as the basis for forming the 3D conformal inner liner surface. Once completed, the unit graph structure is copied and populated throughout the selected host surface following the UV map shape and, for clarity, only the centre role of graph units are shown in Fig. 3a.

Employing 3-matic in this way demonstrates that cell structures can conform to the surface curvature with minimal steps; however, because of how the UV pattern is mapped onto the surface, cell widths become variable following the curvature of the shape. Again for clarity, only the centre row of unit cells along one direction of

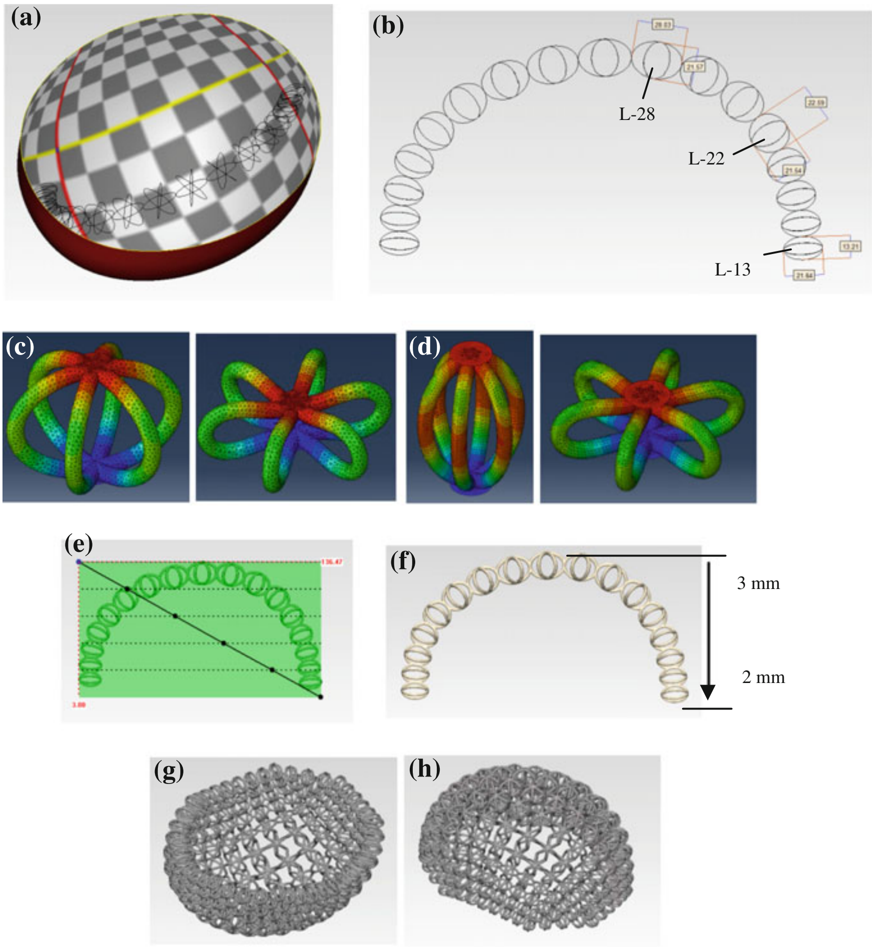

Fig. 3 Illustration of conformal cellular structure helmet liner modelling steps in 3-Matic^{STL} software. **a** UV pattern display on the surface along with *center row* of conformal graph units, **b** Front view of conformal cell graph units showing the degree of deformed shapes from *top* to the *edges*, **c** L-28 cell unit: initial and final deformed shapes in FEA modelling, **d** L-13 cell unit: initial and final deformed shapes in FEA modelling, **e** Applying linear gradient thickness function along one axis in 3-matic, **f** Created solid structure with gradient wall thickness with 3 mm at the *top* and 2 mm at the edges, **g** Completed conformal cellular structures with gradient wall thickness (*Left* Inside and *Right* Outside views)

the liner inner surface is shown, along with the sizes of three selected cells, in Fig. 3b. The resultant structure shows that the cell width close to the crown (upper) area of the helmet liner is stretched to 28 mm (hereafter termed ‘L-28’), whereas the cells approaching the liner base are compressed to a near-elliptical shape (minimum = 13 mm, ‘L-13’). The cell identified as L-22 remains closest to the original, 20 mm width.

It is apparent that the severity of shape changes and the variable dimensions are caused by the steep curvature of the host surface; however, in applications that necessitate uniform *structural* wall thickness (e.g. 20 mm, as here), this approach to generating a conforming surface will incur an inconsistent mechanical response. Depending on the application, achieving consistent energy absorption may well be desirable (as per this application, designing for head protection). The only remaining variable design parameter (realizing the graph structure is now defined) is the individual *cell* wall thickness. The effect of wall thickness on the structural rigidity is now to be investigated using Abaqus finite element analysis software, focusing on 3 units (L-28, L-22, L-13) that can be broadly considered as representative of all cells. Material properties were assigned describing laser-sintered Luvosint X92A-2, which is characterised as a Mooney_Rilvin two-constants hyperelastic material model. Tetrahedral element shapes were used in all meshing, with appropriate edge lengths. Each cell base is fully constrained, resisting a 15 mm compressive load applied to the highest node. Applying a 3 mm wall thickness to cell L-28, a 7.6 N load was required to achieve 15 mm compression. Now, by employing the *linear gradient* function (a newly added function in 3-matic^{STL} 10), the wall thicknesses of the inherently-stiffer L-22 and L-13 cells were automatically varied, to achieve a comparable mechanical response. Cell L-22 required a wall thickness equalling 2.75 mm, whilst L-13 required a 2.25 mm wall thickness. The initial and deformed shapes of L-28 and L-13 are depicted in (Fig. 3c, d). It should be noted that the geometry and material are non-linear, meaning the force-displacement curves exhibited non-linear fashions, though similar trends.

Once appropriate thicknesses are known, the graph units in 3-matic are processed with linear gradient thickness function assigning 3 mm at the top and the 2 mm at the bottom edge along one axis (Fig. 3e) and Fig. 3f shows the corresponding solid model. Due to the symmetric nature of the helmet shape the same gradient thickness is applied accordingly to the rest of the inner-liner as shown in Fig. 3g.

3 Overcoming Existing Technical Limitations by Developing New Software Code

Our above research has highlighted that commercially available solutions lack the complete functionality required to create a consistently conformed hemispherical cellular structure. We now describe the outcome of applying a script written in-house.

3.1 Cellular Design in 3D Studio Max

To find a solution to the distortion of the conformal pattern at the edges (due to a planar projection onto a spherical surface), we developed a custom script within the Autodesk 3DS Max modelling environment [15]. A similar cellular unit was

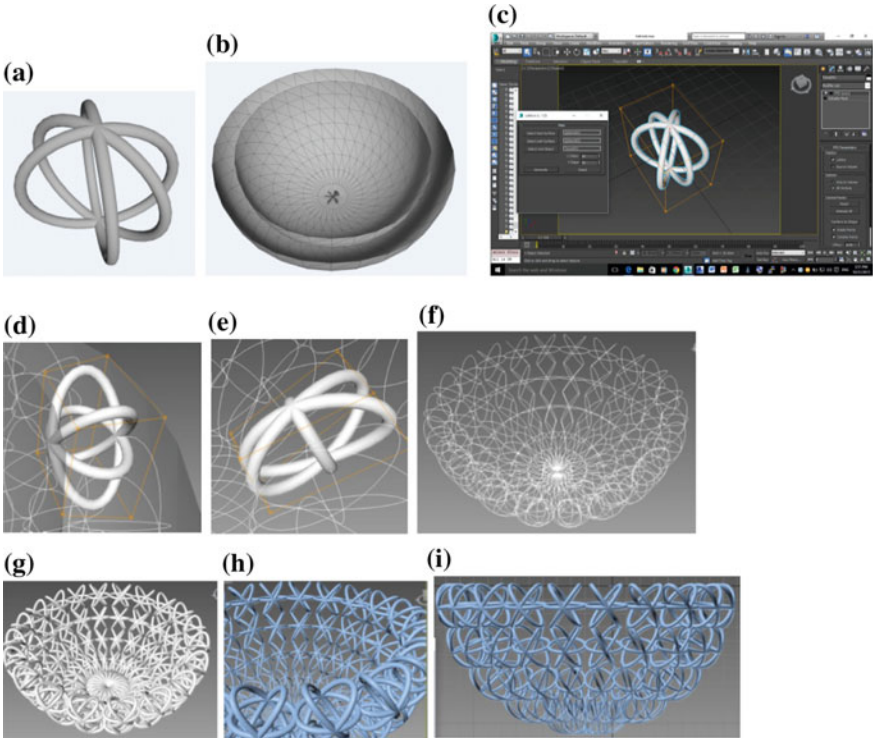

Fig. 4 Illustration of conformal cellular structure helmet inner-liner modelling steps in 3D Studio Max Software. **a** TT—3 mm, **b** Two hemispheres, **c** FFD modifier in 3D Studio Max, **d** Cell position between two host surfaces, **e** A distorted cell located near the crown region, **f** Conformal cellular structures in wireframe format, **g** Conformal cellular solid structure, **h** Gradient wall thickness in 3D view, **i** Gradient wall thickness in front view

modelled from 3 intersecting tori (Fig. 4a). Two non-uniform rational basis spline (NURBS) surfaces were created in the shape of two hemispheres (representing the liner), to host the cellular units (Fig. 4b). The script proceeds by asking the user to select the host surface (e.g. liner outer shell), the limit surface (e.g. the inner shell) and the cellular unit to be replicated (e.g. the tori mesh). It then requires the quantity of units to replicate along each of the u and v parametric directions of the surface. The script then installs a freeform deformation (FFD) modifier on the cellular unit (Fig. 4c). As the unit is placed in the desired position, the FFD modifier allows it to deform its shape to fit between the outer (host) and the inner (limit) surfaces (Fig. 4d). As one can predict, as the cellular unit is replicated towards the pole of the sphere, the distortion becomes more severe due to the fact that the same number of units are packed into an increasingly smaller circumference (Fig. 4e). The final result is a set of inter-connected cellular units that are constrained by the two surfaces (Fig. 4f). It is important to note that the script can function with any free-formed open or closed NURBS surface and thus allows for a high degree of flexibility. Figure 4f, g show the completed structure in wireframe format and the corresponding solid structure respectively. To replicate the cellular units in the same way as the two previous examples the U and V directions can be reversed. One advanced function being investigated enables assigning the thickness across the structure in a gradient function (Fig. 4h, i). The functionality of this in-house script is currently being expanded to accept a higher number of boundary surfaces. Due to the intellectual property associated with this work the full details of the script cannot be described at this stage.

4 Discussion

This paper aimed to perform a technical evaluation of commercially available software, before performing comparison with our in-house code embedded with 3D Studio Max. Here, we aspired to conform a planar surface of a cellular structure to achieve a hemispherical shape.

Using the Creo software a TT cellular skelton was translated into a solid 3D unit, with an array of units populated onto a circular planar that was warped to form a semi-sphere shape. The advantage of using parametric software such as Creo is that once the conforming process is complete, the cell and helmet dimensions can be parametrically varied to achieve a new structure. In this way different sizes of liners, or variable cell shapes, can be realised in minimal steps. A shortcoming is that the cell shapes are deformed following the curvature of the sphere when wrapping the cellular structure around the head, meaning non-uniform wall thicknesses are generated in each cell unit. Though a sphere shape can be warped from a circular shape, more complex shapes such as ovals would be very challenging to achieve following this approach. Furthermore, high computational resources are needed to handle complex solid geometries that are composed of many b-rep surfaces [12].

In the 3-matic software, a cell structure is a network of curves rather than a solid geometry and so it can be a challenging task to create even a moderately complex shape. Unlike Creo, 3-matic is not parametric-based and the cell shapes and dimensions are difficult to alter; hence, best practice is to import a cell constructed in conventional software. After the curves are converted into a graph structure, the two dimensional patterning and three dimensional patterning is sequentially followed to form an array of conformal graph structures. At this stage the deformation of each cell shape is observed on graph unit, with 3-matic ensuring that the specified cell wall thicknesses are retained through the conforming process. Additionally, 3-matic also enables the development of functionally graded structures, through using the linear gradient thickness function.

In 3D Studio Max the option is already available to form a skin cellular (i.e. lattice) structure. To enhance its cellular function to form a solid cellular structure required development of a custom script. Here, we demonstrated an identical conformal liner integrated with TT cell structure. The advantage of using this script is that two opposite surfaces can be used as host surfaces in a single step, with the edges of the cell structures aligned to the curvatures of these surfaces. This is particularly useful when the two surfaces are not entirely parallel, with the cell edges being stretched to maintain its structural rigidity along the edge. Further work is being performed so that all boundaries can be used as host surfaces, to create complete cell units which are close to the edges. The flexibility of the developed script enables assigning thickness across the structure (based on the number of row or column) in a step function or as input parameters (e.g. maxThickness, minThickness) in a linear function. In future work we aim to advance the script to demonstrate assigning localised thickness, so that we can better control the stiffness and compliance regionally while maintaining the smooth transition across the neighbouring cellular units.

To conclude, in all the CAD techniques employed, the deformation of each cell is unavoidable after contouring and the only way to minimise the differences in the mechanical response is by adjusting the wall thickness across the structure. Our in-house script, embedded within 3D Studio Max, demonstrated greater functionality by performing the initial construction of 3D wireframe cellular units in conforming the shape of the surrounding boundaries, the addition of wall thickness with different cross-sectional profiles, and the assignment of variable wall thickness across the structure in both linear and non-linear fashions.

In the near future, we intend to perform FEA impact simulation on these structures to further optimise in fulfilling the desired functionality. The helmet liner demonstrated in this work possess only 13 % volume fraction at 3 mm wall thickness, and weighs around 200 g based on an AM elastomer material. Increasing the thickness to 5 mm (to absorb higher impact energy) results in 35 % volume fraction with 730 g weight. EPS foam helmet liners have far higher volume fractions, meaning that AM represents a more sustainable manufacturing process for this sector.

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An Investigation into the Quasi-Static Response of Ti6Al4V Lattice Structures Manufactured Using Selective Laser Melting

Qixiang Feng, Qian Tang, Shwe Soe, Ying Liu and Rossi Setchi

Abstract Ti6Al4 V (Ti64) lattice structures manufactured using selective laser melting (SLM) have been used in fields such as aerospace and medical science due to their exceptional light weight, corrosion-resistant capability and biocompatibility. In this study, the mechanical properties of octahedral-type Ti64 lattice structures under quasi-static loading conditions was investigated. The initial stiffness, ultimate strength and ductility of the structures with different aspect ratios were evaluated and compared using experiments and quasi-static finite element analysis (FEA). The results demonstrated that the experimental data and FEA were in good agreement. The initial stiffness and strength of the octahedral lattice structures improved significantly as the strut aspect ratios decreased; however, the poor ductility evident in all the samples showed no obvious relationship to the aspect ratios, which means that the geometrical sizes had little effect on the brittle behaviour of the Ti64 lattice structures fabricated using SLM.

Keywords SLM technique · Ti6al4V · Lattice structures · Finite element analysis

1 Introduction

Metallic lattice structures are widely used in the aerospace and automobile fields due to their multifunctional properties, including high strength-to-weight ratio, energy absorbance, sound proofing and electromagnetic wave shielding. Of the many kinds of bulk materials used for fabricating metallic lattice structures, titanium alloy shows two main superior mechanical and multifunctional properties. First, the tensile strength of Ti6Al4V (Ti64) is around 900 MPa while its density is 4.43 g/cm^3, which means that Ti64 has a relatively high strength-to-weight ratio. Accordingly,

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Ti64 lattice structures show promise in lightweight design applications. Second, Ti64 has good biocompatibility and corrosion-resistance properties, therefore biomedical implants, such as artificial bones and scaffolds composed of Ti64 lattice structures, have been widely used in surgeries and the orthopaedic industry.

Nevertheless, because of the poor machinability of Ti64 material, it is difficult to fabricate Ti64 lattice structures using conventional manufacturing processes such as casting, but selective laser melting (SLM) offers a promising alternative process for manufacturing intricate components. As a high-energy laser beam is used during the manufacturing process, the density of titanium parts fabricated using SLM can reach up to 99.9 % [1] and their strength can reach up to 1300 MPa [2]. Consequently Ti64 lattice structures show good mechanical properties and few defects. From our literature survey, compared with metallic lattice structures made from other metallic materials such as stainless steel 316L, Ti64 structures showed brittle behaviour in mechanical tests, which indicates that Ti64 structures are more applicable in static or quasi-static loading conditions. Therefore, the key element of this study was to determine the initial stiffness, ultimate stress and ductility of Ti64 lattice structures under loading conditions.

In this paper, the mechanical properties of Ti64 lattice structures manufactured using SLM under quasi-static compression loading conditions are presented. The rest of the paper is structured as follows: related literature is reviewed in Sect. 2. In Sect. 3, quasi-static tensile and compression tests on Ti64 tensile specimens and lattice structures, respectively, will be discussed, and a quasi-static finite element analysis (FEA) will be detailed in Sect. 4. The results, analysis and related discussion will be presented in Sect. 5. Finally, the conclusions and suggestions for follow-up studies will be listed in Sect. 6.

2 Related Works

Metallic lattice structures can be fabricated using conventional techniques [3–5], which usually demand casting in multiple steps or using a tooled approach [6]. With the application of selective laser melting (SLM) and electron beam melting (EBM), metallic lattice structures can be manufactured within a relatively short space of time, and the size of the unit can be on the micrometer scale. By far, metallic powders suitable for manufacturing lattice structures include stainless steel 316L [7–10], CoCrMo [11], AlSi10 Mg [12] and Ti64.

Due to their light weight, high strength, and heat and corrosion resistance, Ti64 lattice structures are deemed exceptionally multifunctional solutions that can be used in aerospace, maritime and medical applications. Cheng et al. compared the compression behaviour of two kinds of cellular structures, namely stochastic foam and a lattice structure fabricated using EBM. α’ martensite was found primarily in the struts using optical observation, and the lattice structures exhibited higher specific strength than their foam counterparts [13]. Yavari et al. studied the fatigue behaviour of four different lattice structures and determined the corresponding S-N curves. A power law was found, and this may help estimate the fatigue life of Ti64 lattice structures manufactured using SLM [14]. Sun et al. analyzed fracture loads of octahedral Ti64 lattice structures in an experimental study and theoretical calculation, and the results revealed an exponential relationship between the fracture loads and the porosity of the structures. Moreover, the authors pointed out that the Ti64 structures manufactured via SLM were brittle [15]. Challis et al. studied high-porosity lattice structures using a topology optimized method with maximized stiffness. The structures showed superior specific strength and stiffness when the relative density was in the range of 0.2–0.8 g/cm^3 [16]. The mechanical response of Ti64 lattice structures manufactured by SLM in quasi-static and dynamic compression tests was examined by Merkt et al. Compared to the experimental results with the mechanical response of stainless steel 316L lattice structures, the Ti64 structures showed brittle behaviour and low energy absorption capabilities [17].

The aforementioned literature shows that Ti64 lattice structures exhibit brittle behaviour, thus the Ti64 lattice structures are more suitable for supporting applications where special requirements, such as an extremely light weight or corrosion resistance, are demanded. In this scenario, it is necessary to determine the static or quasi-static properties of Ti64 lattice structures. Conducting large numbers of experiments is time-consuming and expensive since current SLM processes are still inefficient. As FEA can reduce the number of laboratory tests, in this study, the experimental studies and FEA were combined to determine the mechanical response of the Ti64 lattice structures.

3 Experiments

To study the mechanical behaviour of Ti64 lattice structures, quasi-static tests were conducted and are discussed in this section. First, the Quasi-static tensile tests on standard tensile specimens were conducted first. This specimens were manufactured using SLM and the aim of the tensile tests was to obtain the material parameters of the Ti64 parts fabricated using SLM, which were also used as the input of the material properties required in the subsequent FEA process. Then Quasi-static compression tests were conducted on lattice structures which were manufactured with the specimens in the SLM machine. Thereafter, based on the load-displacement data recorded by the testing machine, the nominal stress-strain curves of the samples were obtained which shows the mechanical properties of the lattice structures.

3.1 Material Characterization

To obtain the material properties of the Ti64 parts manufactured using SLM, three tensile tests were conducted first. The standard specimens were made in accordance with ASTM E8/E8 M-15a: Standard Test Methods for Tension Testing of Metallic

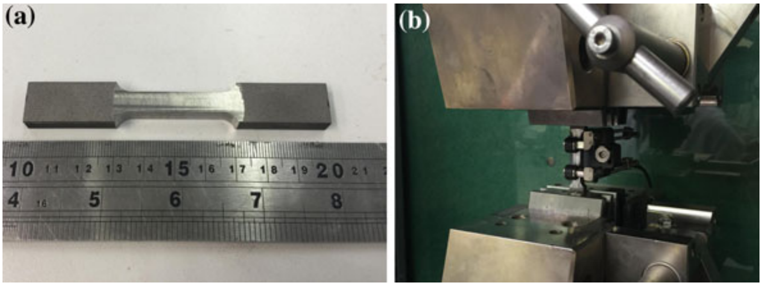


Fig. 1 **a** A Ti64 tensile specimen fabricated using SLM; **b** the quasi-static tensile test on a tensile specimen

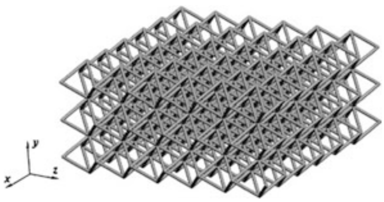
Materials. The sizes of these specimens were matched to the required dimensions for a sub-sized specimen. The powders used for fabricating the specimens were made from Ti64. The equipment used for fabricating these samples was an EOS M280 SLM system located in the Additive Manufacturing Research Center of Chongqing University, China. The effective build volume was 250 mm × 250 mm × 325 mm.

Three tensile specimens were oriented horizontally in the chamber of EOS M280, then stress-relief heat treatment was applied to these specimens. The specimens were then machined to attain the required sizes of the ASTM standard. To avoid possible slippage during the tensile test, sand blasting was applied to the surfaces of the specimens that were in contact with the clamps, as shown in Fig. 1a. Thereafter, the three specimens were subjected to a quasi-static loading rate of 2 mm/min. As Fig. 1b shows, the tensile machine was equipped with an extensometer to obtain accurate strain data.

3.2 *Design of the Lattice Structures and Compression Tests*

The lattice structures investigated in this study were octahedral lattice structures, which are also called body-centred cubic (BCC) structures [6]. As Fig. 2 shows, the design space of all the octahedral units is a cube with an edge length L of 5 mm. For each structure, the number of units in the three orthogonal directions (length × width × height) was 6 × 6 × 3 mm. We defined the aspect ratio (AR) of each structure as the ratio of the strut length l to the strut diameter d. By then

Fig. 2 CAD model of the Ti64 octahedral lattice structure



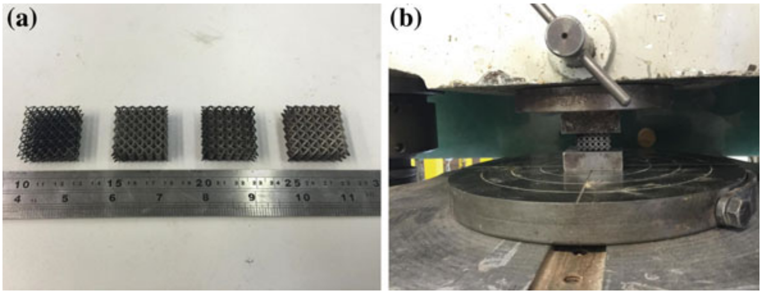


Fig. 3 **a** Ti64 lattice structure samples fabricated using SLM; **b** the quasi-static compression test on a Ti64 structure sample

specifying that the AR equalled 10, 8, 6 and 4, respectively, we obtained four different octahedral lattice structures. The CAD models of these structures were designed in Creo 3.0 software. These structures were subsequently manufactured using the EOS M280 system with the build orientation along the Y axis, followed by a stress-relief heat treatment.

Figure 3a and b shows the Ti64 samples manufactured using SLM and the quasi-static compression test on a universal test machine separately. The lattice samples were loaded in the build direction during SLM, namely the Y-axis direction. The displacement rates of the crosshead were set to 1 mm/min. The displacement and reaction force of the crosshead were recorded during each compression test in order to plot the nominal stress–strain diagrams.

4 Numerical Modelling

As mentioned above, detailed stress distribution of lattice structures can be obtained using FEA although it is difficult to observe this using experimental measures. In this study, the quasi-static compression simulation on the octahedral lattice structures was conducted using ABAQUS commercial finite element software.

For each structure, the simulation approach, called the continuum elements model, was carried out. To reduce the computation time, one-quarter of the symmetrical model of each structure was built. The multi-units model could thus reveal the interaction between the adjacent units under compressive loading conditions. Two rigid surfaces called top and bottom, respectively, were modelled in the part module, and they were used to simulate the crosshead and substrate in the compression tests. Rigid and non-friction contact conditions were set between the rigid surfaces and the structure. As Fig. 4 shows, two reference points (RPs) were placed at the centre of the rigid surfaces. The one on the top surface applied the displacement boundary conditions to the models, and during the simulation, the displacement of the top surface was recorded. The reaction force applied in the RP on

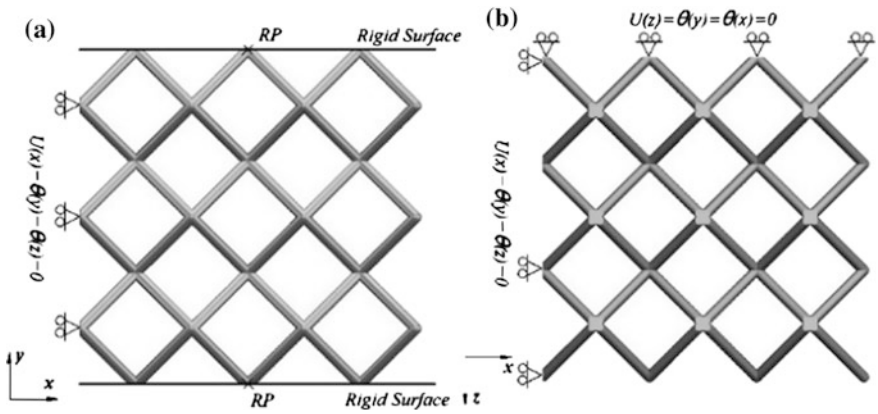


Fig. 4 A FEA model of the Ti64 lattice structure

the bottom surface was also recorded. A dynamic explicit analysis step was established for each FEA model after the default initial step. In this step, called 'press', the upper rigid surface shown in Fig. 4 moved downwards and compressed the structure, while the bottom rigid surface was fixed during the whole process. Moreover, the material models were assumed to be isotropic, and the von Mises yield criterion was used in the FEA analysis. The material parameters were obtained via the above tensile tests, and the resultant nominal stress–strain curve is shown in Fig. 5a. The true stress–strain data converted from the nominal stress–strain data were used as the material properties in each FEA process.

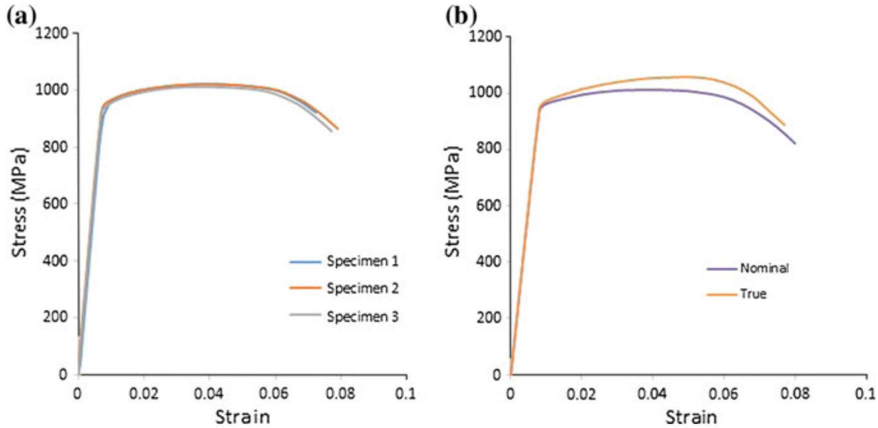


Fig. 5 **a** Nominal stress–strain curves of three tensile specimens; **b** Nominal and true stress–strain curves of Ti64 obtained via quasi-static tensile tests

5 Results and Discussion

In this section, the mechanical properties of Ti64 tensile specimens and lattice structures manufactured using SLM are presented. As aforementioned, the key mechanical properties of Ti64 fabricated in this process, namely its elastic modulus, yield stress and ultimate stress, are obtained by conducting quasi-static tensile tests. Thereafter, these parameters are used in the FEA models of lattice structures to obtain the corresponding FEA results. The results are then compared with the experimental data obtained from the above-mentioned compression tests to analyse the mechanical response of the octahedral-type lattice structures manufactured using SLM.

5.1 Characterization of Ti6Al4V Tensile Specimens

As Fig. 5a shows, three nominal stress–strain curves illustrate good repeatability. From the nominal stress–strain data of specimen 2 in Fig. 5b, the elastic modulus was calculated as 118 GPa, the yield stress was 944 MPa and the ultimate stress was 1058 MPa. The true stress–strain curve was obtained based on the minimal curve, the plasticity of the Ti64 specimens could subsequently be obtained, as Fig. 6a shows. It also illustrates that the tensile specimens were ductile since the ultimate plastic strain under tensile loading was close to 0.07. As Fig. 6b demonstrates, the necking phenomenon occurred on the tensile specimen, which correlates with this conclusion.

5.2 Mechanical Response of the Lattice Structures

It is usually time-consuming and computationally expensive when FEA is conducted on lattice structures. For the FEA models in this paper, each one-quarter

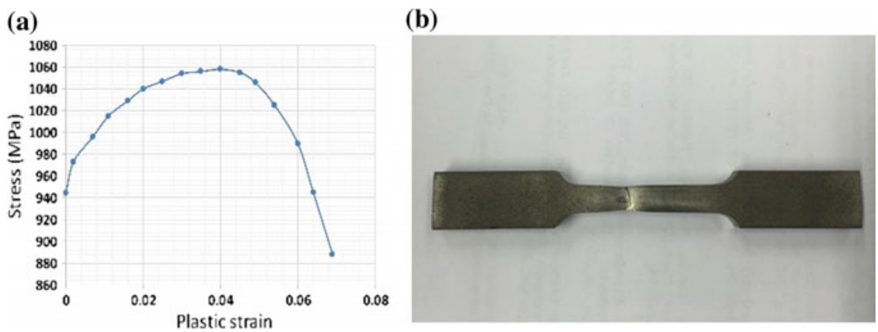


Fig. 6 **a** Necking phenomenon of a Ti64 tensile sample and **b** the true plastic strain curve obtained via the tensile tests

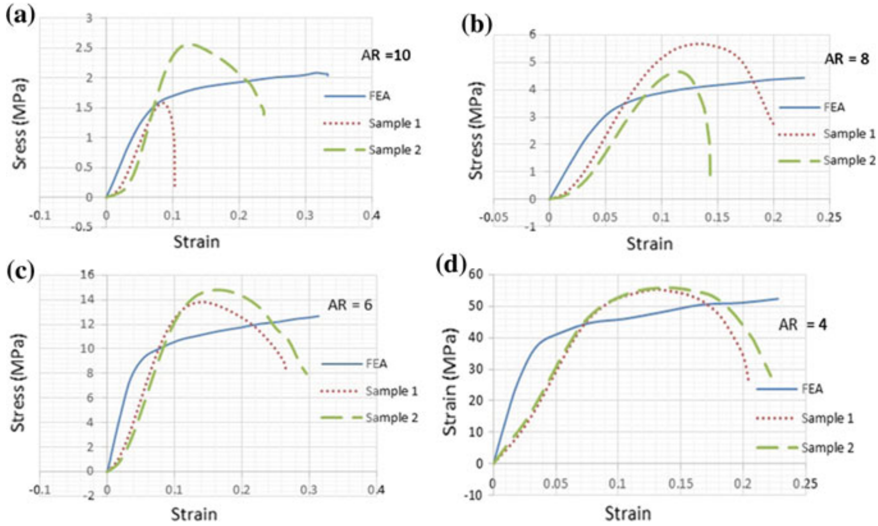


Fig. 7 Nominal stress–strain curves of the Ti64 structures

model contained 27 units, and the overall number of meshes exceeded 100 thousands. To reduce the computational cost and avoid possible convergence problems, an explicit dynamic procedure was used, and a corresponding quasi-static analysis was conducted. According to the ABAQUS help manual, this method requires fewer system resources than the implicit procedure. Once the simulation had been completed, the internal energy (ALLIE) and kinetic energy (ALLKE) of the model during each analysis procedure were compared to ensure that the ALLKE was significantly smaller than the ALLIE (each ALLKE was less than 5 % of the corresponding ALLIE).

Figure 7 shows the nominal stress–strain curves of the four octahedral lattice structures. The curves obtained from the FEA illustrated that the structures deformed approximately linearly before and after the structures began to yield, which means that the deformation was in accordance with the ideal linear hardening model. The experimental curves showed that the structures deformed non-linearly prior to the linear elastic stage due to the full contact condition between the samples and the crosshead was established during each experimental compression process. Moreover, the experimental curves dropped sharply just after the ultimate strength (UTS) point, which means that these Ti64 lattice structures were brittle compared with the lattice structures made from 316L steel. Additionally, the compression strain corresponding to the UTS of all the samples was around 0.1, and there was no obvious relationship between this strain and the aspect ratio, therefore, the change in geometrical sizes had little effect on the ductility of the Ti64 structures made via SLM.

The initial stiffness and the UTS of the structures obtained through the FEA and compression tests are shown in Table 1 (where S1 and S2 represent two identical samples at the same aspect ratio). The values of initial stiffness in the table were

Table 1 The initial stiffness and UTS of the Ti64 lattice structures

Aspect ratio	d (mm)	Stiffness (MPa)			UTS (MPa)		
		FEA	S1	S2	FEA	S1	S2
10	0.43	27	25	50	1.7	1.6	2.55
6	0.54	70	70	65	3.6	5.7	4.6
8	0.72	220	160	160	11.5	13.8	14.8
4	1.08	1321	800	800	48.23	55.8	56

obtained by calculating the slope of the corresponding stress–strain curves in a linear elastic range. For each stress–strain curve obtained via FEA, the UTS value was estimated and deemed the value in accordance with the strain where the experimental UTS values were obtained. As the aspect ratio decreased, both the stiffness and UTS of the octahedral structure increased. Since the stiffness and UTS values predicted from the FEA study correlated with the experimental data (Fig. 5 and Table 1), the quasi-static analysis was a useful measure in estimating the mechanical response of the Ti64 lattice structures manufactured using SLM.

Importantly, the discrepancy between the FEA and the analysis should not be ignored. As the FEA was conducted on ideal CAD models of the structures, errors existed between the sizes of the CAD models and the actual sizes of the corresponding samples. As the accuracy of the metal parts manufactured by SLM was around 0.1 mm, the smaller the strut sizes, the higher the percentage of errors encountered. Therefore, to minimize errors between the FEA and testing results, measures should be taken to improve manufacturing accuracy. Another noted discrepancy was between the mechanical responses of two identical samples with the same aspect ratios. As the aspect ratio decreased, i.e. the diameter of the strut increased in this scenario, the discrepancy of the initial stiffness or UTS between the two testing samples decreased, which showed better repeatability. For samples at aspect ratio equals 10, the design value of the diameter of inner struts are around 0.43, however, the real diameter values of the samples encounter highest percentage of error compared with that of other samples at lower aspect ratios. From Table 1, variation of diameters causes prominent variation of stiffness values. Therefore, significant discrepancies are caused at high aspect-ratios. This phenomenon revealed that the accuracy of the current SLM process significantly influenced the mechanical responses of the Ti64 lattice structures.

6 Concluding Remarks

In the present study, the mechanical response of Ti64 lattice structures with four aspect ratios manufactured using SLM under compression loading condition was examined. Tensile specimens and octahedral lattice structures made of Ti64 powder were manufactured using the EOS M280 laser melting system. Thereafter, stress-relief heat treatment was applied to both the tensile specimens and lattice structures. The property of the bulk material was determined through the quasi-static tensile tests on the tensile specimens in accordance with ASTM E8/E8 M. The tensile tests revealed that the elastic modulus was 118 GPa, the yield stress was 944 Mpa, the UTS was 1058 MPa and the bulk material had good ductility as the maximum strain exceeded 0.07. The quasi-static response of the lattice structures were then evaluated using compression tests and FEA. The results obtained from the two measures showed that the initial stiffness and UTS of the octahedral structure improved significantly as the aspect ratio decreased from 10 to 4, and the FEA analysis provided stiffness and UTS values that correlated with the sample experiments. The compression strain, which corresponded to the UTS for each structure, was around 0.1 in spite of its aspect ratio, and shortly thereafter each structure began to fracture. This phenomenon revealed that Ti64 lattice structures fabricated via SLM present brittle behaviors, and geometrical sizes have little effect on their ductility.

Future work will focus on the effects of the SLM process in order to minimize the discrepancy between the experimental results and the FEA prediction. The geometrical errors of the Ti64 lattice structures caused by the SLM process will be compared with corresponding CAD models, and then the FEA models will be adjusted according to the errors in order to predict accurately the mechanical properties of the Ti64 lattice structures.

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A Bottom-up Design Framework for CAD Tools to Support Design for Additive Manufacturing

Steven Goguelin, Joseph Michael Flynn and Vimal Dhokia

Abstract Additive manufacturing (AM) technology is enabling a platform to produce parts with enhanced shape complexity. Design engineers are exploiting this capability to produce high performance functional parts. The current top-down approach to design for AM requires the designer to develop a design model in CAD software and then use optimization tools to adapt the design for the AM technology, however this approach neglects a number of desired criteria. This paper proposes an alternative bottom-up design framework for a new type of CAD tool which combines the knowledge required to design a part with evolutionary programming in order to design parts specifically for the AM platform.

1 Introduction

Research and development progress in additive manufacturing (AM) technologies has given rise to an increased output of functionally usable parts. There are a number of advantages to AM in comparison to conventional subtractive manufacturing techniques, such as milling, turning or drilling, including increased shape complexity, functional complexity, material complexity and hierarchical complexity, [1] which are resultant from a layered manufacturing process.

AM does not however, come without disadvantages. There are limitations and constraints including the size of the build geometry, a slow build speed, support structure requirements, residual stress considerations, and post-processing requirements for functional surfaces. A skilled and experienced designer can mit-

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igate against a lot of the aforementioned limitations but there will always be a compromise between the selection of additive and subtractive methods.

The ability to manufacture practically any shape, regardless of complexity has allowed the designer to build complex freeform surfaces and also optimize designs for particular criteria, such as reducing weight or increasing stiffness. Computational support is required to perform these structural and topological optimization processes and the final designs often look very different to the initial CAD models proposed by the designer during the embodiment phase.

The current top-down approach of designing a part with conventional subtractive manufacturing techniques in mind and then topologically optimizing the design for an AM platform leads to an increased development time of a final part suitable for manufacture and the resulting designs are not developed for all criteria that is required for a functional part.

In contrast to a top-down approach, bottom-up approaches seek to commence a part design with the manufacturing platform in mind; for the AM platform the designer will consider the design for additive manufacturing (DfAM) rules throughout the part design process. There are a number of challenges to altering from a top-down to bottom-up design mentality, particularly in terms of computational design support.

This paper will discuss the requisite criteria that a designer has to consider when designing for AM. Secondly, it will explore the benefits of developing a design strategy for bottom up development for AM, and finally, a theoretical CAD framework for designing for AM will be hypothesized and proposed.

2 Review of Design for Additive Manufacturing

Before it is possible to develop a new framework for DfAM it is necessary to consider existing work in defining design rules across multiple AM platforms and also in computer aided design tools for AM.

2.1 A Review of Existing Design Rules

In order to establish the limitations of the AM technologies, a number of researchers and AM machine manufacturers have investigated the development of design guidelines and design rules for various platforms in order to help the designer create parts that have a higher chance of a successful build. Guidelines have been produced for Fused Deposition Modelling [2, 3], Selective Laser Melting [4], Direct Metal Laser Sintering [5–8], Stereolithography [9], Electron Beam Melting [10].

These design rules are specific to processes and are also often specific to machine setups and calibrations; as such industry and makers often create their own set of design rules which enhance the capability of their particular machines. In addition, the design rules are focused primarily on the manufacturability of the part. In reality, the manufacturability is only one element of the design process and it is important to consider other elements in the incorporation for component design rules. Furthermore, these ideas require consolidation onto a platform in which they can be used to aid the designer during the product design process.

There have been a number of papers highlighting redesign for AM case studies, Becker et al. [11] proposed a redesign strategy for a mix device following the creation of basic design guidelines, reducing the number of parts and minimizing assembly time. Another example of part redesign involved the redesign of a bracket for manufacturing using an EBM process [12]; through parametric optimization and structural validation the authors were able to improve the manufacturability of the product on the AM platform.

2.2 A Review of Additive Manufacturing Computer Design Tools

AM computer aided design tools can be split into two categories: top-down and bottom-up CAD tools. Top-down methods aid the designer after they have developed their final design solution. These include tools for assessing the manufacturability of the part [13], suggesting the most suitable additive process [7], or aiding in material selection for the part [14].

Alternatively, bottom up CAD tools help the designer to explore the design solution space and generate designs based on the specified input criteria. Bottom-up CAD tools can also be referred to as generative design tools. Research into generative design tools has been used to design architectural structures [15], and a generative design tool has been proposed for part design based on user specifications [16].

There is also one example of a tool which exists between these two regions. Krish [17] proposes a tool which will generate further solutions based on the original computer model developed by the designer. Results show that it is possible to use native CAD systems for design exploration, however the size of the search space is limited using this method.

3 Framework for a New Additive Manufacturing CAD Tool

Building on the literature review for current design rules, it is necessary to consider how these rules can map into computation design support tools to aid the designer. A proposed theoretical framework will now be presented.

3.1 Additive Manufacturing Design Considerations

The AM design rules discussed in the literature review (Sect. 2.1) have helped the designer to understand the limitations of the machines and the manufacturability of AM parts. It is now important to develop these design rules into a format which can directly support the designer throughout the design process.

Table 1 shows the design considerations which are necessary for the designer to consider during the development of the final part design. The considerations have been divided into process and geometric considerations. In order to successfully design for AM both categories must be considered equally during part design.

The cognitive burden on the designer can be demanding as a vast number of qualitative and quantitative considerations have to be considered during the conceptual and embodiment design stages. The design considerations in Table 1 can be subdivided into quantitative and qualitative categories. Quantitative rules make use of physical laws and can be defined using equations and algorithms. They are extremely useful in defining the product design specification as they can be used as metrics to evaluate the success of the final design.

Qualitative considerations, on the other hand, cannot be defined using mathematical techniques, they are instead based on the designers experience and common sense reasoning. This tacit knowledge is difficult to capture, however qualitative design considerations are paramount to the development of parts and products that humans will enjoy interacting with, developing product families and ensuring company design regulations are incorporated into a design.

In addition to the design requirements, the designer also has to be aware of the manufacturing methods which are available and also the limitations of these processes. Typically, the designer will have a limited number of manufacturing machines available. It would be beneficial for the designer to specifically design parts for the available resources. Table 2 shows a non-exhaustive list of the design considerations a designer may have to scrutinize in a typical part design.

The proposed CAD tool framework will have to help the user develop the problem space and consider the manufacturing constraints on the system when proposing the design solutions. Furthermore, the design tool must help to remove the cognitive burden on the designer by reducing the number of design considerations that must be examined.

Table 1 Selection of process and geometric considerations when designing a part

Process considerations	Geometric considerations
Build strategy	Functionally graded materials
Build orientation	Dimensional accuracy
Residual stresses	Part consolidation
Support strategy	Optimization techniques
Layer thickness	Strength
Production speed	Stiffness
Surface quality	

Table 2 Design considerations which may be required and traded-off against one another when designing a part

Quantitative	Qualitative	Available resources
Support strategy	Testing requirements	Additive process
Build orientation	Maintenance strategy	Subtractive process
Build quantity	Inspection routine	Inspection process
Stress analysis	Aesthetics	Materials available
Geometry	Human-part interface	Post-processing tools
Layer thickness	Recyclability	
Cost	Ergonomics	
Mass		
Temperature range		
Humidity range		
Interfacing components		
Machining cutting forces		

3.2 The Role of Computation in Design for Additive Manufacturing

The development of computer-aided-design tools has led to designs of far greater complexity. The ability to make rapid changes to designs, or achieve feedback on a design from another person at a click of a button has decreased product development time. Interfacing part modelling software with analysis tools such as finite element analysis, and computational fluid dynamics also allows verification of designs computationally, reducing the amount of wastage, both material and time, from manufacturing unsuccessful prototypes.

Whilst CAD systems have doubtless increased productivity and improved design output they are not without flaws. The disadvantage of CAD systems have been explored by Robertson and Radcliffe [18]; traditional CAD modelling tools can lead to a reduction in creativity throughout the design process. Three critical limitations to current CAD systems will now be explored.

- Circumscribed Thinking: The complexity of the design that is created is proportional to the designer proficiency in the modelling tool. The design output from the designer is currently limited by their knowledge of the CAD system as opposed to their cognitive creative output. This has huge implications when designing specifically for AM. The shape complexity, part consolidation, and optimization techniques which are required to optimize parts for AM require expert level skills in the CAD system to be able to develop designs which exploit the full potential of the machines. Designers will have to develop years of experience on the modelling tools before they can begin to design parts which are optimized for the AM process.

- Premature fixation: As computer models become more complex the designer feels less incentive to make major design changes. This circumstance tends to occur in less experienced designer rather than expert designers, however, typically there will be changing requirements throughout the design process. The ability to develop designs which balance a vast number of design criteria by exploring the extensive solution space is imperative to exploiting AM technology.
- Cellular structures: AM machines can print at various levels of hierarchical complexity. The features can be designed with shape complexity across multiple scales [1]. Honeycombs, lattices and other shape elements can be designed into a part for weight reduction and to demonstrate variable properties across a part using one material. Depending on the size and shape of a part the amount of cellular features may be in the order of hundreds of thousands; traditional CAD systems cannot perform geometric modelling on this number of geometric elements.

In order to alleviate a number of the aforementioned problems a new framework for a CAD tool will be explored.

3.3 CAD Support for Bottom up Design for Additive Manufacturing

It is becoming clear that designers require some degree of computational support in order to take full advantage of AM platform capabilities. However, it is not yet clear as to the level of support that is actually required. The four categories below shows the variance of human/computer interaction (HCI) that are possible; moving down the categories there is a clear shift from top-down to bottom-up design strategy. Figure 1 depicts the mapping of varying levels of HCI onto a continuous scale.

1. Designers use the CAD tool as they see fit, however, the CAD system does not give any user feedback on the design or manufacturability based on any defined requirements. The designer can then choose to analyze the design in external programs. This is the current standard for computer aided solid modelling for AM.
2. The designer proceeds with CAD in the detailed stage, however, there is an addition to the CAD system which allows the designer to select an option for a

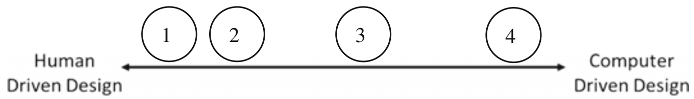

Fig. 1 Levels of HCI that are possible in CAD systems

computer program to evaluate certain criteria or give advice on which process best suits the part. This is a prime example of top-down design and it is the current state-of-the-art.

3. The designer defines a set of inputs which are fed into the computer algorithm to generate a set of design solutions. Incrementally the designer evaluates the design solutions which have been given and these inputs are then used to define the next set of design changes. The more iterations specified by the designer the closer algorithm will get to the specific user requirements [19]. This is an example of generative design technology and moves into the bottom-up design bracket.
4. The designer defines the input parameters of the system. A computer algorithm will then generate all possible solutions that fit the design requirements. From the initial results, the algorithm will evaluate the best solution depending on the optimization criteria specified by the designer. The output of the algorithm will give the designer one option which will be optimized for a particular function. This is an example of autonomous design. The principal challenge of fully autonomous design is that it is impossible to capture all of the qualitative, tacit knowledge that the designer possesses and as such the output designs will not cater toward human interaction.

Whilst the second level of HCI is useful for the evaluation of a design, it does not solve the aforementioned issues surrounding top-down design. The most sensible proposition for new CAD tools must therefore be the third level; a method in which an algorithm creates a design, however the design inputs are driven by the designer. This design method will now be explored further with a proposition of a new generative CAD tool framework.

3.4 A Collaborative Generative CAD Tool for Additive Manufacturing

The generative design framework can be described by three interlinked stages as shown in Fig. 2. The primary stage describes the development of the problem space. The proposed CAD tool incorporates a series of databases of criteria which may be specific to the part. The databases include the design considerations shown in Tables 1 and 2 and could also contain company specific parameters to ensure design continuity throughout an enterprise.

The designer is then required to extract the relevant design parameters from the databases. One of the challenges in AM that requires attention is the understanding of the trade-offs in the technology. Consider a design which is optimized for weight reduction and as such a lattice structure is employed in the design, whilst this is appealing and solves the weight issue, the part becomes challenging to inspect and cannot therefore be certified for use as a functional component. The designer will have to create a hierarchical structure of priorities they desire for the design.

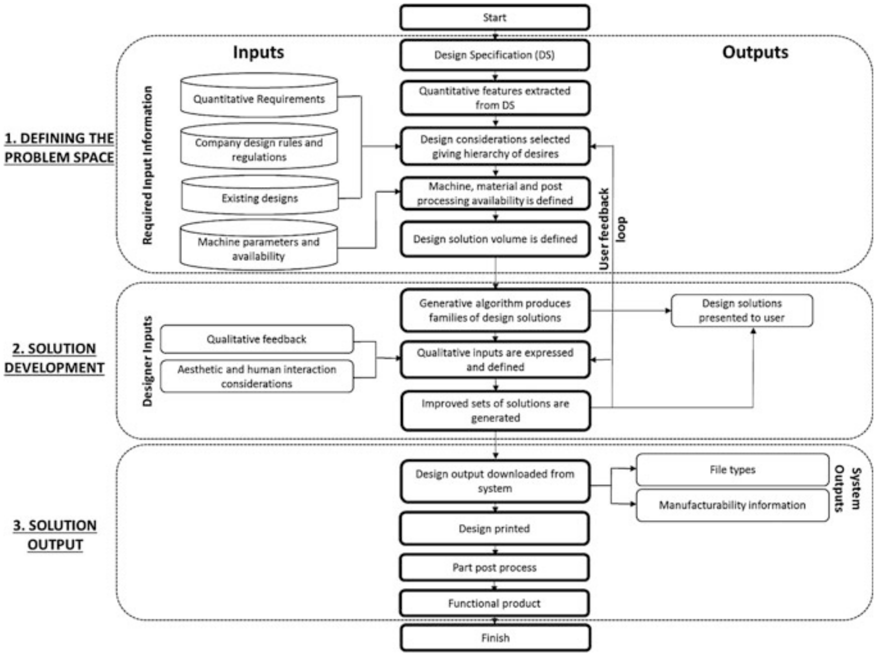

Fig. 2 Schematic of the proposed CAD framework including relevant system and designer inputs and outputs

The designer then determines the machine and material availability for additive, subtractive and post-process technologies in order to develop specific solutions for these technologies. This is important as optimized designs will be based on specific material and machine combinations.

A design solution volume is defined as the volume to which the generative software can apply material. From this information a generative algorithm can be used in conjunction with optimization techniques to deposit material within this solution volume.

The second stage of the framework is termed solution development. Here solutions are developed which are optimized for the trade-offs selected from the hierarchy stated in the previous stage. At this stage in the concept generation, it is solely the quantitative parameters which will be considered.

By taking advantage of multi-criteria evolutionary algorithms the designer can program many inputs into the system, with the design evolving within the solution space converging as close as possible to the criteria hierarchy intended by the designer. At this point the designer has the option to impart some of the qualitative knowledge they possess with regards to part aesthetics and human interaction with the part. The designer will also have the opportunity to vary input parameters from the databases in the primary stage.

The CAD tool will then use the best solution(s) as selected by the designer from the first generative stage as the new evolutionary input(s), generating more appropriate designs based on the modified input parameters and defined qualitative information improving the capture of the designer's initial intent. This approach is then repeated, within a user feedback loop, until a satisfactory design can be delivered from the system. The ability and speed of recompiling design solutions is integral to the system. The overall quality of the design solution is dependent on giving the designer the ability to redefine the problem space as more knowledge is gained about the design direction.

The final stage of the framework is labeled design output. In order for the design tool to be useful the design would have to be exported in files types currently used in AM, e.g. .STL, .AMF. in conjunction with the AM file formats the tool should also give some indication of the correct build orientation and build strategy along with suitable post-processing techniques in order to finish with a functional part.

3.5 Disadvantages to Bottom-up Design Methods for Additive Manufacturing

Whilst a bottom-up design approach would give the designer a much greater scope when designing for AM, it is important to consider the potential drawbacks of using this approach. Firstly, bottom-up design is not suitable for all design applications. Consider the design of a turbine blade for the aerospace industry, many decades of development have shaped the design of a turbine blade and it would be more suitable to design this component from a top-down approach in order to rapidly converge on the optimum solution.

Secondly, HCI is necessary for the generative design tool however, human input also leads to a reduction in speed of the algorithms and also a lack of consistency in design selection. It would be impossible to generate learning algorithms if the user defined the same result with a different satisfaction rating across multiple iterations [19].

4 Conclusions and Future Perspectives

This paper proposes a shift in thinking from top-down to bottom-up design methodology with particular emphasis to AM. Whilst a bottom-up approach to design will not be suitable for all design applications, systems which require optimized shape design for different categories, the proposed bottom-up design methodology may provide improved solutions when designing for AM.

Building upon current research, design inputs required to successfully design a part for the AM platform have been assessed and these can be split into process and geometric requirements, in order to gauge the feasibility of employing these criteria into a design tool, they were further split into qualitative and quantitative considerations. It was deduced that the proposed CAD framework would have to utilize both human and computation knowledge to develop a viable solution to a component design problem.

By considering the advantages different levels of HCI, a new theoretical CAD framework has been proposed which aims to exploit the advantages of AM technologies whilst alleviating some of the disadvantages that exist with using conventional CAD tools during the design process. By encouraging the user to define the correct hierarchical problem space and employing advances in multi-objective evolutionary computing, the designer will be able to search greater areas of the solution space and generate more appropriate and satisfactory design solutions.

Whilst a new AM perspective has been defined in this paper, further work must be undertaken before this kind of design tool is applicable for complex three-dimensional part design. Experimental work has to be undertaken in order to establish a full set of part design requirements for the system knowledge database, alongside developing methods for capturing design information from existing designs. Furthermore, defining the relationship between machine parameters and their effect on a final part must be defined.

Evolutionary models need to be optimized for design in order to be able to fully explore the solution space and new ways of utilizing these algorithms for the generation of three-dimensional part design need to be established.

It is acknowledged that there are many issues that need to be addressed before this kind of tool can be used effectively, however, the framework in this paper can be seen as a possible method of improving a designer's ability to capture and utilize the full potential offered by emerging AM technologies.

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A Surface Modification Decision Tree to Influence Design in Additive Manufacturing

Eleanor Rose Gordon, Alborz Shokrani, Joseph Michael Flynn, Steven Goguelin, Jack Barclay and Vimal Dhokia

Abstract Additive manufacturing (AM) presents a very different set of design challenges to traditional manufacturing. Layer-wise building brings about issues with residual stresses and support requirements which lead to failures during processing of poorly-designed parts. Additionally, there is a need for post-processing due to poor part quality, which adds another process to the chain with its own unique design limitations. This paper discusses the issues surrounding designing for AM and the subsequent post-processing. A future vision is proposed for the selection of post-processes and the relative design adjustments to accommodate the chosen techniques. A decision tree is presented as a framework for process selection based on part requirements. Although at present, the data necessary to realize this vision is incomplete, with further research into the capabilities and design constraints of different post-processes, this approach could provide a systematic method for integrating design for post-processing with AM design.

Keywords Additive manufacturing · Design for additive manufacturing · Post processing · Surface modification

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1 Introduction

1.1 Benefits and Uses of Additive Manufacturing

The geometrical freedom provided by additive manufacturing (AM) makes it an attractive technology to a number of industries. In many cases, layer-wise building significantly reduces waste material, part weight, and number of parts which can improve functionality [1]. The two main types of metal AM process are powder bed fusion (PBF) and directed energy deposition (DED). In PBF, parts are created by powder distributed across a bed in layers which is subsequently melted by a heat source such as a laser or electron beam to produce the geometry. In DED techniques, the material, which can be either wire or powder, is melted and deposited simultaneously. PBF is more suitable for producing fine features with greater geometrical accuracy, while DED processes have faster build speeds [1], making the choice of technique very application-specific.

AM comes with its own complexities and challenges which differ from those of traditional manufacturing processes [2]. Due to the relative infancy of the technology, design rules and methods for AM are still being discussed and developed. The quality of as-built parts is inappropriate for many applications, and often post-processing is required [3]. AM can be used as the primary manufacturing process or as part of a chain of processes, as shown in Fig. 1. Although several definitions of hybrid manufacturing exist [4], this is one way of differentiating between AM with post processing, sequential manufacturing and hybrid manufacturing. In the context of this paper, subtractive manufacturing is the addition or removal of features, whereas post processing is used to modify existing features. Sequential manufacturing involves all three stages of manufacturing, but has no capability to return to a previous stage. Hybrid manufacturing has the capability of alternating between additive and subtractive manufacturing any number of times prior to post-processing. The focus of this paper is design for AM with a post-processing phase.

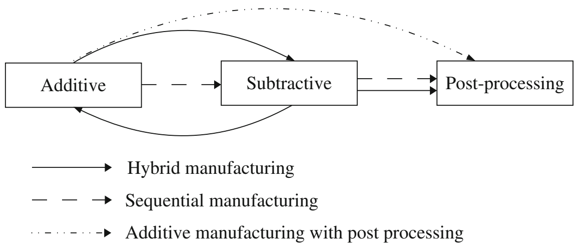


Fig. 1 Diagram identifying the focus of the paper in the context of the research area

2 Challenges in Additive Manufacturing

2.1 *Part Quality*

Due to the complex thermal interactions that occur in AM processes, a number of challenges arise which require technology-appropriate designing and process-planning. The AM technology employed, specific processing parameters and part orientation all influence the residual stresses, microstructural formation and surface quality.

Residual stresses are caused by the thermal gradients experienced during build and can cause part deformation and even failure [5]. The poor surface quality produced by AM is partly caused by the stair-step effect, which is a result of the zeroth order approximation of geometry in layer-wise building. Additionally, wire-fed processes tend to produce parts with a high surface waviness [6], and powder-based processes lead to high surface roughness due to balling and the partial melting of powder particles [1]. The latter is most evident in PBF processes where powder in the surrounding bed is fused to the part by residual heat, particularly at steep angles where step edges are close together. Figure 2 illustrates the effect of partially melted powder on as-built surfaces. The roughness parameter, Ra, of an AM part can vary between approximately 7–25 μm depending on the AM process used, the processing parameters and the part geometry [1]. The surface roughness influences several functional properties including fatigue resistance, frictional properties, and heat transfer, as well as introducing the risk of powder becoming loose, for example, in the human body [7]. Consequently, until there is a significant step-change in the resolution of AM technology, post-processing will be a necessary step in the additive process.

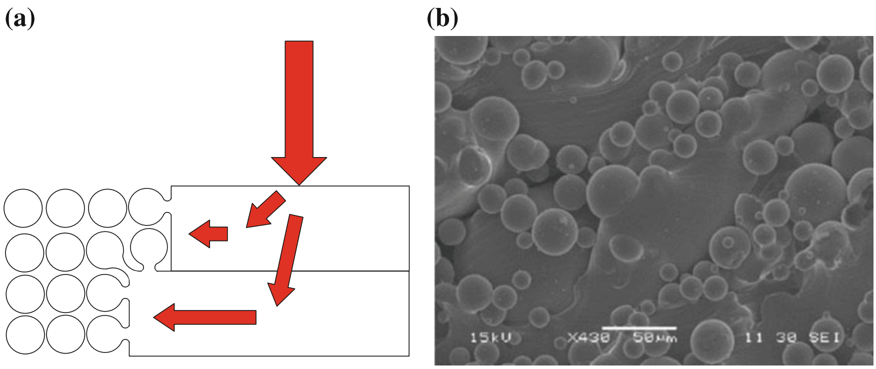


Fig. 2 Partially melted powder as **a** Diagram at step between layers adapted from [8] and **b** Micrograph of an AM part

2.2 Designing for Additive Manufacturing

In AM design, there is a requirement to support overhanging surfaces at less than approximately 45° from the horizontal plane to prevent deformation due to gravity and residual stresses. Part re-orientation, sacrificial supports and self-supporting structures can help to achieve this. Some AM technologies also have feature size limitations such as particularly thin walls which can be subject to deformation under the re-coater force and small bore holes which can become clogged by adhered powder [9].

At present, design for AM often involves re-designing parts which were originally designed for a conventional method such as machining. The re-design usually involves a topological optimization approach, allowing the designer to maximize stiffness or loading capabilities of a component whilst reducing weight [10]. This system produces an organic or freeform structure which is then adjusted using AM design rules. Therefore, post-processing is often an afterthought. As industry moves away from the re-design approach towards standardized design methods for AM, post-processing needs to become a more integrated consideration at an earlier phase of design. Although some researchers mention the need for designing with a post-processing perspective, very little information is provided as to how this might be achieved beyond removing support structures and allowing for loose powder removal by designing in, for example, escapement holes. Each post-process has its own unique challenges for component design. It is important to consider firstly which post-processing techniques are appropriate for a part's function, and then to identify the impact of that choice on the design.

3 Post Processing in Additive Manufacturing

Depending on the application of a part, a number of different post-processes may need to be undertaken following the AM build process. Figure 3 shows the typical order of post-processes for an AM component. Each post-processing phase has different options for the technique employed and different design considerations.

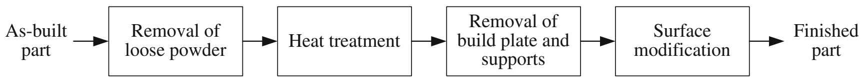


Fig. 3 Diagram of post processing stages for AM parts

3.1 Removal of Loose Powder

Loose powder removal in PBF processes is usually a manual process with the complexity being dependent on the part geometry. However, sometimes it can be necessary to use a more controlled or aggressive method such as shockwave cleaning or dry-ice blasting to remove this powder [11]. It is important that parts and support structures are built to allow the removal of loose powder from any internal cavities.

3.2 Heat Treatment

The specific heat treatment procedure is application and material specific, however, in general, a low temperature heat treatment is used to relieve stresses to avoid deformation upon removal from the build plate. A high temperature process is used to achieve more appropriate microstructures for the required mechanical properties [5], and hot isostatic pressing (HIP) is used to heal pores and improve ductility and fatigue resistance [1].

3.3 Removal of Build Plate and Supports

Build platform removal can involve a manual process, wire-EDM or a band saw depending on the geometry, material and support structure [1]. The removal of the part from the build platform should be considered at an early stage of design. The support structure also needs to be designed appropriately to support the geometry whilst remaining accessible and breakable by the chosen removal technique. Self-supporting structures can be used to reduce waste material and post-processing but can also increase part weight unnecessarily. Having sacrificial supports can create support witnesses upon removal. If the presence of support witnesses would detrimentally impact part functionality, these also require removal either as a separate manual stage or by using an appropriate surface modification technique.

3.4 Surface Modification

Surface modification and feature finishing is used to achieve the required surface quality and can consist of one or multiple techniques. This is a developing field because of the part quality requirements of industries and the desire to fully exploit the benefits of AM. The geometrical freedom offered by AM means that no one-size-fits-all solution exists. Table 1 gives details about individual surface

Table 1 Surface modification processes reported as being used on AM parts

Post process	Application	Benefits	Complexities	References
Mechanical				
Machining (M)	To achieve specific geometrical tolerances and fits beyond the ability of AM e.g. mating faces	Reduces Ra (0.4 µm) and increases fatigue life. Can improve dimensional accuracy and achieve specified tolerances	Can involve complex programming, requires line-of-sight, fixturing and metrology considerations	[12]
Grinding (G)	Finishing of flat, sloped or slightly curved surfaces	Can achieve very low Ra values (0.34 µm) and remove partially melted powder	Unable to finish complex, highly curved or inaccessible features	[13]
Shape adaptive grinding (SAG)	Removal of partially-bonded powder particles and reduction of Ra on complex, freeform, external surfaces	Different grit sizes can achieve a range of Ra values down to as smooth as 3 nm	Can involve complex programming, requires line-of-sight, fixturing and metrology considerations	[14]
Grit/bead blasting (GB/BB)	Regularly used for cleaning/finishing of AM parts for non-critical applications. Can be a manual or controlled process	Can remove unsintered powder and reduce Ra to 3.87 µm	Can produce uneven finish if manually controlled, requires line-of-sight and can result in embedded finishing media	[13]
Waterjetting (WJ)	Can be used as finishing process to reduce waviness of wire-fed AM parts	No embedded media as with sand/grit blasting	Requires line-of-sight and may increase roughness by creating small fractures and surface cavities	[6]
Abrasive flow machining (AFM)	Used to reduce roughness inside cavities and channels by forcing abrasive media through the workpiece	Can achieve high surface quality in complex internal channels (Ra = 0.1 µm)	Embedding of abrasive media can occur, and edges and corners can be rounded, fixturing can be complex to avoid media leakage	[15, 16]

(continued)

Table 1 (continued)

Post process	Application	Benefits	Complexities	References
Thermal				
Laser polishing (LP)	Potential to create smooth surfaces within an AM machine following build by selectively re-melting surface material	Can achieve low Ra (<2 µm) with high selectivity on flat, sloped and curved surfaces	Difficulty in achieving uniform intensity profile on sloped/curved features can lead to deviation from designed geometry	[17]
Electron beam irradiation (EBI)	Used for large-area thermal finishing of simple, complex or textured line-of-sight surfaces	Can produce uniformly smooth surfaces (Rz = 0.7 µm) and heal surface cracks and pores	Requires line-of-sight, is non-selective, and impacts surface microstructure	[6, 18]
Chemical				
Hydrofluoric Acid etching (HF)	Used for non-selective finishing of entire freeform surfaces, lattices and internal features	Fast etch rate compared with alternative chemicals, capable of non-line-of-sight. finishing	Extreme health and safety concerns, effectiveness limited by oxidation	[3, 19]
Electrochemical				
Electrochemical polishing (ECP)	Used as non-selective finishing technique on freeform structures	Can achieve smooth surface morphology when adhered particles are pre-removed	Electric field is limited inside deep cavities and therefore internal finishing may not be uniform	[13, 19]
Plasma polishing (PP)	Used as non-selective finishing technique on freeform structures	Less volatile chemicals and more aggressive finishing than ECP	Electric field is limited inside deep cavities and therefore internal finishing may not be uniform	[13]

modification processes which have been reported in literature for the finishing of AM parts. Each finishing process has limitations and complexities which impact on design. By considering the implication of finishing process selection on part design, further design iterations are triggered to accommodate these additional requirements.

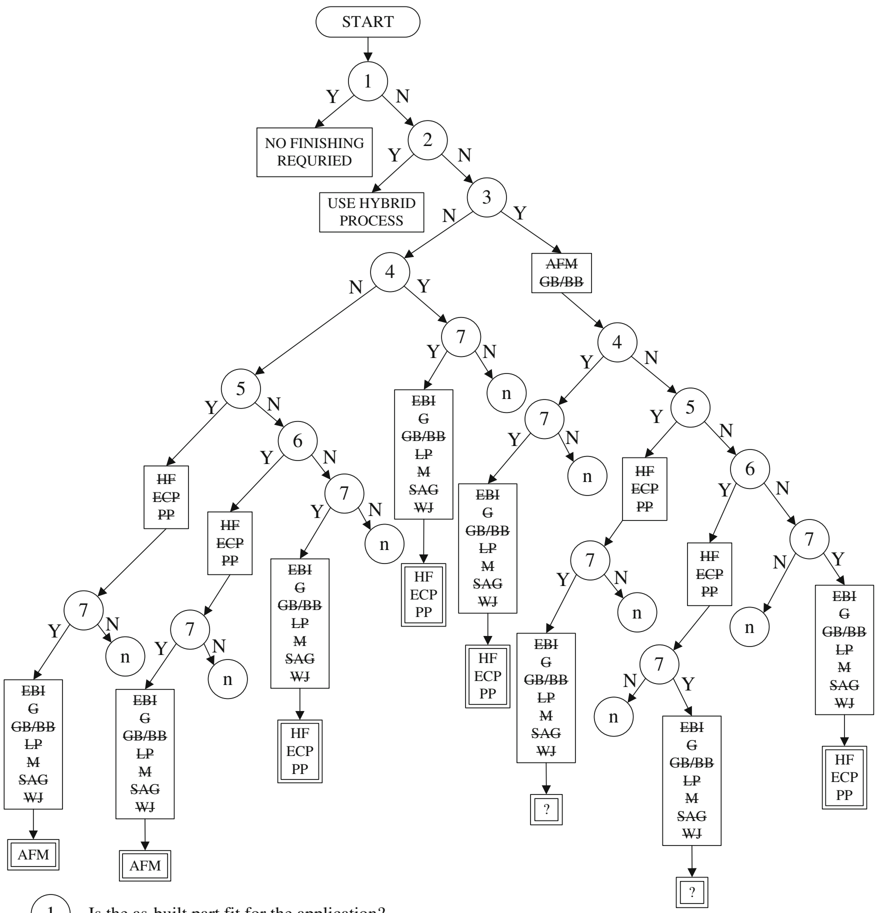
Currently, the main post-processing considerations at the design stage include loose powder and support removal, but surface modification is often an afterthought. This is most likely because it has the greatest range of processes and the decision is very dependent on part application and geometry. It is, however, for this same reason that it is important to consider it as early as possible in the design phase. There is currently no standard selection process for surface modification techniques or guideline for designing with them in mind. The next section of the paper proposes a vision for the selection of processes and adjustment of part design to accommodate the selected techniques.

4 Vision for the Future of Design for Additive Manufacturing

The proposed medium-term vision for AM design involves considering post-processing and its impact at the early design stage. The first phase is a decision making process which is driven by a database of the available post-processes and their capabilities. The desired geometry and part requirements are used to answer questions which lead to candidate solutions for surface modification of a particular part or feature. The second phase consists of adjusting the part design to accommodate for the selected post-processes or to modify the part such that different processes become candidates.

Figure 4 outlines a proposed decision tree for selecting suitable candidate surface modification techniques for an AM part. Although this decision tree is incomplete, it gives the basic framework which could be populated with further information and more detailed questions. Where the questions lead to an 'n', it is expected that this would begin a line of more detailed questions about specific part requirements. However, in order for the decision tree to be completed, more detailed information is required about the techniques to compare their appropriateness for different applications. Further questioning would consider surface roughness parameters, tolerance requirements and any preferential treatment which occurs during the processes. Other considerations would include part material, the selectivity and predictability of finishing required and any mechanical properties which may be influenced during processing.

The decision tree, once populated with further data, could be used as the framework of a process selection software. Instead of directly interacting with the decision tree, the user would be presented with a series of yes/no questions in the order dictated by the decision tree. The answers to the questions would cause the exclusion of any inappropriate processes. This would eventually lead them to an interactive screen highlighting the candidate solutions to the physical problem. However, there are many additional important considerations which could then be explored at this stage including economic factors, the speed of processing, integration of the processes with existing processes in the AM chain and any environmental factors



1 Is the as-built part fit for the application?

2 Does the part require tolerances tighter than what is achieveable by the AM process?

3 Is contamination from embedded finishing media a concern for the application of the part?

4 Does the entire part require surface finishing?

5 Is it detrimental to the part function to finish the entire part?

6 Are there any features which would be sensitive to non-selective finishing e.g. high aspect ratio features?

7 Are there any non-line-of-sight features requiring finishing?

⋮

n Continue with more specific questions about part requirements.

AFM – Abrasive Flow Machining
EBI – Electron Bean Irradiation
ECP – Electrochemical Polishing
G – Grinding
GB/BB – Grit Blasting/Bead Blasting
HF – Hydrofluoric Acid Etching
LP – Laser Polishing
M – Machining
PP – Plasma Polishing
SAG – Shape Adaptive Grinding
WJ – Waterjetting

Fig. 4 Decision tree of surface modification techniques for AM parts including consumables, power and health and safety implications. The selection of surface modification techniques would then allow identification of any design modifications required to accommodate them to ensure that the final part meets its requirements. These may include the addition of stock material both globally and locally to allow for uniform or preferential material removal, fixturing and location requirements, and any improvements to accessibility.

It can be observed that there are some combinations of answers to the questions which lead to no known surface modification techniques, marked by a question mark. This is where there are gaps in the capabilities of existing processes. At present, if this is the result from following the decision tree, a part would need to undergo fundamental design changes to make it appropriate for an existing technique.

5 Discussion

At present, making informed selections of candidate techniques following a specific combination of answers is difficult due to the limited data available about existing techniques. Directly comparable experimental analysis of the processes on different geometries and materials would help to populate a database. If the decision tree were developed further with more detailed questions about surface requirements, this would provide a powerful tool to improve the design process. It would help identify requirements which cannot be met by existing processes, allowing any needs for significant re-design to be highlighted without wasting material. One example of this may include non-line-of-sight features. Many companies wish to avoid the use of HF due to its extreme health and safety implications, however, at present it is the most versatile non-line-of-sight process. ECP and PP are possible solutions but may suffer from loss of effectiveness due to limitations of the electric field. Hence, in some cases, the use of HF is unavoidable without significant part re-design. The decision-making process should, however, be future-proofed for any newly developed process to be included without changing of the format. Selective finishing processes are more complex to compare due to the greater range of control and surface modification mechanisms. Selective processes are more likely to be feature-specific rather than part-specific, requiring decisions to be made for individual features. This decision tree therefore requires adaptation as it evolves to accommodate feature-based finishing, using real parts as case studies.

The ability to identify design considerations following process selection would allow design for post-processing to be more integrated with the design for AM process. However this also requires more detailed analysis of the surface modification techniques. At present, HF is one of the most researched processes, and it has been shown that with a specific set of process parameters (such as concentration and treatment time) the material removal can be predicted allowing the design to be adjusted to achieve the desired geometry and surface roughness in a lattice structure [3]. This research is critical in relation to designing from a post-processing perspective, and needs to be mirrored for other processes if the vision is to become a reality.

6 Conclusions and Future Work

AM design methods currently have limited acknowledgement of the design implications of surface modification techniques, even though it is crucial for many critical applications, and will be for the foreseeable future. This paper proposes a vision for the future of design for AM, involving a surface modification decision tree which helps to identify candidate solutions and provides information about design considerations for the chosen processes. However, in order to make this a reality, there are areas of research requiring significant development.

To fill some of these knowledge gaps, there is a requirement for more detailed quantitative analysis of the physical capabilities and the economic and environmental implications of surface modification techniques. Additionally, the development of new surface modification techniques is required to meet geometrical and surface roughness requirements which are currently not possible.

Future work in this area will involve further developing the decision tree, enabling it to identify suitable candidate techniques for parts with specific, feature-based or global requirements. Multiple case studies will be used to create a robust line of questioning which could be used as the framework for a process selection software.

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Additive Manufacturing Simulation Using Signed Distance Fields

Jack Barclay, Vimal Dhokia and Aydin Nassehi

Abstract Manufacturing simulation is important to build understanding of a process. It is especially useful for learning about AM processes that are time consuming, expensive, and may have an environmental impact. Generating or modifying explicit meshed geometry during a simulation can be a computationally expensive task. Other geometric representations, such as implicit surfaces, make these types of topographical transformations easier and may be more suited to making as-manufactured models from simulations. Here, it is shown that signed distance fields are a flexible and efficient representation format for AM process simulation. The suitability of ray marching for the visualisation of these geometries is also shown. These simulation techniques enable quick feedback from design or process plan modifications to geometric model validation.

Keywords Additive manufacturing · Implicit geometry · Distance fields · Ray marching

1 Introduction and Motivation

The proliferation of Additive Manufacturing (AM) in recent years has seen the development of many platforms and processes that enable complex parts to be built quickly and efficiently. The introduction of any new technology requires a period of time where it can be explored and experimented with to build understanding of the process and of its parameters. AM technologies make it much easier to produce complex part geometries, to the point where traditional design rules have to be reconsidered and redefined.

The best approach for learning more about a process is often experimental. However, this is not always practical; it is time consuming and expensive to run tests on many AM machines. Instead, the goal is to create computational models

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and simulations that allow for many quick tests to be run and for the results to be relevant to the real life application. This means that process parameters can be optimised offline so that time on the machine can be minimised, which, for example in the case of powder bed metal additive machines, could have adverse environmental effects. It is noted that, currently, there are no commercial simulation systems that exist for AM users [1] and it would be very useful to have a simulation system for AM that is similar to VERICUT for CNC machining processes.

In this research, a system is explored that uses implicit surface representations as an alternative to explicit meshed geometry. It is the authors opinion that these are the better option for generating in-process geometry through simulation of the manufacturing process. Inspiration is taken from earlier work on high-accuracy NC milling simulation [2] where each tool movement has a distance field swept profile subtracted from the initial billet. This is extended for AM by building geometry from the accumulation of small additive depositions.

1.1 Geometric Design Challenges for Manufacturing Simulation

Most commercial CAD/CAM systems use boundary representations (B-reps) to define their geometric models [1]. B-reps are an easy and intuitive method to use when designing, but they are not optimal for simulating manufacturing processes. As the tool path length increases, the in-process model becomes very complex and it can take a long time to simulate [2].

One big problem is in the use of as-designed models and not as-manufactured models. By not building the model alongside a simulation of the process, the variations between what is intended and what will actually be produced are not considered. An as-manufactured model shows artefacts from layer stair-stepping and can be used in analysis to see how the manufacturing process has affected the material properties and structural performance [3].

The STL file format is still the de facto standard for representing object models for additive manufacturing. A STL file description uses a polygonal mesh to define geometry, but beyond that is not capable of representing colour, material, or other metadata. To address some of these concerns the AMF file format has been proposed [4]. Regardless of input file format, the layer-by-layer additive process requires slices of the geometry to be taken to generate tool paths that will be run on the machine.

Finite Element Methods use polygonal or polyhedral meshes and are good at calculating small continuous deformations on models. However, this assumes that the topography remains constant [5] and this assumption does not hold true for large or discontinuous deformations. For a manufacturing simulation, in which geometry should be grown or destroyed according to the process, this is problematic. Mesh generation, refinement, and decimation, are computationally intensive tasks, but are unavoidable when aiming to simulate additive and subtractive manufacturing processes. To perform this topographical restructuring at an interactive rate, alternative methods to represent geometry will be explored.

1.2 Geometric Representations

A geometric entity can be represented using many different techniques. These techniques divide into being continuous or discrete, and explicit or implicit. A sphere centred at the origin with radius r can be expressed in the *implicit* form

$$f(x, y, z) = x^2 + y^2 + z^2 - r^2, \tag{1}$$

or in the *parametric* form using spherical coordinates

$$\boldsymbol{f} : (\theta, \phi) \mapsto \begin{cases} x := \rho \cos(\theta) \sin(\phi) \\ y := \rho \sin(\theta) \sin(\phi) \\ z := \rho \cos(\phi) \end{cases} \tag{2}$$

where

$$\rho \in [0, \infty], \quad \theta \in [0, 2\pi], \quad \text{and} \quad \phi \in [0, \pi].$$

An explicit representation requires evaluating the range of the parametric function. For every possible input parameter value, there will exist a point on the surface of the geometry being defined. By systematically using values across the whole domain of the input parameters, a set of points can be produced that sample the mathematically defined surface. These can then be connected to form a polygonal mesh; a list of triangles that tessellate to form a watertight solid. This is a convenient way of representing objects and most popular computer graphics software packages will have support for using polygonal mesh file formats. However, using a polygonal mesh can make it more difficult to perform some geometric operations. For example, collision detection requires testing against many triangle primitives and mesh refinement often requires expert manual input to ensure a sensible mesh. There are alternative representation formats that may be more useful in some such occasions.

An implicit representation of the sphere is given by the level-set of the implicit function. Traditionally this level is 0, hence zero-level set, i.e. all the values that make $f(x, y, z) = 0$ lie on the surface of the sphere. This definition is useful because it makes it easy to test whether a selected point is inside, outside, or on a geometric object; point classification is reduced to a simple function evaluation [6].

Implicit representations can also be discretised to reduce the complexity of solving to find the isosurface at every step. Distances are sampled at regular intervals on a uniform voxel grid and the location of the boundary is interpolated from these known data points. One famous algorithm for creating a polygonal mesh from this information is called marching cubes [7]. These discrete methods may be faster to compute and interact with, but they are approximations to the real surface definition. This work proceeds by exploring the continuous implicit representations of geometry and how they can be used to simulate manufacturing processes.

2 Continuous Distance Fields

Distance fields are scalar fields that represent the distance from any point in space to the closest geometric entity. A distance field may represent a single geometric object, multiple objects in a scene, or a combination of objects interacting through Boolean set operations.

The signed distance function for a given set Ω is defined as the function that returns the minimum distance from a point p to the boundary $\partial\Omega$, where the result is positive when p is outside of Ω and negative when it is within. The geometric shape is then defined implicitly as the zero level set $\mathrm{d}(p) = 0$.

$$\mathrm{d}(p) = \mathrm{sgn}(p) \cdot \inf_{y \in \partial\Omega} \|p - y\| \tag{3}$$

where

$$\mathrm{sgn}(p) = \begin{cases} -1, & \text{if } p \in \Omega \\ +1, & \text{otherwise} \end{cases} .$$

Distance fields have been used for collision detection and proximity queries extensively [8]. Distance computations are inherent to their definition and therefore interaction between objects is easily computed. The sustained growth of parallel processing capabilities has helped distance fields to become a powerful tool in the computational toolbox, with real time interaction a possibility on modern graphics hardware.

2.1 Modelling with Signed Distance Functions

A signed distance field can represent any geometry that is defined implicitly. For example, a sphere at the origin is represented by

$$\mathrm{d}_{\mathrm{sphere}}(p) = \|p\| - r_{\mathrm{sphere}}. \tag{4}$$

One such function may define a geometric primitive, but a combination of them must be used in order to produce models of a higher complexity. The three main

Boolean operations used in Constructive Solid Geometry (CSG) are the union $A \cup B$, the intersection $A \cap B$, and the difference $A \backslash B$. When using signed distance functions, these Boolean operations can be implemented using min and max operators [9].

$$
\begin{aligned}
\mathrm{d}_{A \cup B}(p) &= \min(A, B) \\
\mathrm{d}_{A \cap B}(p) &= \max(A, B) \\
\mathrm{d}_{A \backslash B}(p) &= \max(A, -B)
\end{aligned}
$$

These CSG-like operations allow intricate models to be built up using a combination of signed distance fields. Geometry can be created with the joining of individual primitives, as it is with additive manufacturing, or removed by subtracting primitives from the main object, as it is with machining. This forms the basis of the simulations performed for this research.

2.2 Rendering of Distance Fields

To visualise a signed distance function on a screen, a virtual camera is positioned in the world and rays are cast from the camera, through the screen, and toward any implicitly defined geometry that is in view. The image is drawn based on how and what each ray hits in the virtual world, with shading, shadows, and reflections all included if desired.

A ray is cast in order to find the first intersection point between itself and the geometry. This process can be accelerated by using data from the signed distance functions. At a point p it is known that the closest object is exactly $\mathrm{d}(p)$ away, but it is not known in which direction. If travelling along a ray from p in the direction v_d, a step of size $\mathrm{d}(p)$ can safely be taken whilst guaranteeing that no intersections will be missed. This technique is called ‘ray marching’ or ‘sphere tracing’ [10].

2.3 Related Work and Optimisations

Adaptively sampled distance fields, ADFs [11], use a finer sampling mesh in areas of local detail and store the data in an octree-based hierarchy that enables efficient processing and retrieval. This has been used for cutting tool engagement calculations [12, 13] to enable high-accuracy NC milling simulation [2]. Each tool motion command has an accompanying distance field swept profile calculated, with the final part produced from the Boolean subtraction of every profile from the initial billet. To combat additional complexity as the number of swept profiles increases, each new profile can be checked against the others within its hierarchical cell [2]. Those that no longer contribute to the external surface can be culled. This method produces high-accuracy NC simulations, but without using the parallel capabilities of graphics hardware it will still take a long time to run a simulation.

3 Additive Manufacturing Simulation Using Distance Fields

When performing a manufacturing simulation, it is key to have an aim—perhaps something that is being investigated or optimised. These simulations focus on exploring the geometry of AM parts, highlighting the variations between as-designed and as-manufactured parts. The secondary goal is to be able to very quickly explore design and process plan modifications, so the simulation must be able to run in real time. Three simulations have been selected to demonstrate some of the benefits of making simulations using the techniques described in this paper. Following these examples, the limitations of the proposed system are discussed.

3.1 Case 1: A Simple Geometry

The first case is the simplest and looks at a couple of simple components. Figure 1 shows a simple cube and a small pyramid, both made by depositing layers in alternate directions.

The deposition shape for these tests is represented by a capsule shape (cylinder with hemispherical ends). One benefit to using signed distance functions for the definition of these shapes is that this deposition shape can be modified to anything that can be described in implicit form. However, the more complex the signed distance function becomes, the more time it will take to evaluate and, therefore, the slower the simulation will run. This could be an area to explore in future work.

Currently the simulation is clamped to 60 frames per second running at a resolution of 1280×720 on an *Intel Iris 5100* integrated graphics processing unit. At this frame rate, it is possible to move around the virtual world, zoom in/out, fast-forward, pause, and rewind the simulation.

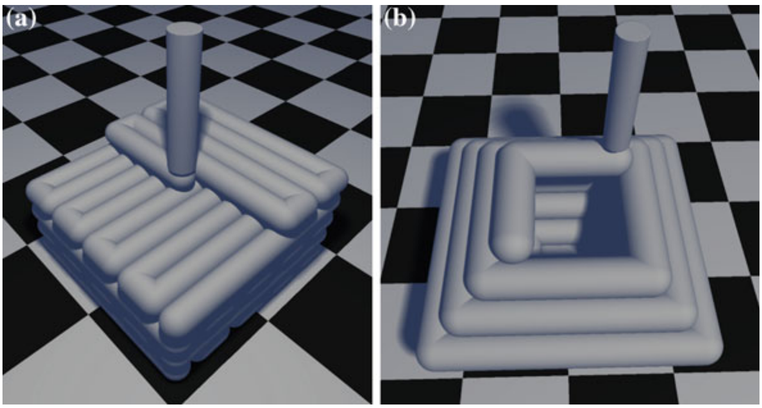

Fig. 1 Simple geometries: **a** a cube, deposited layer-by-layer in alternate directions; **b** a hollow pyramid, created by interpreting G-code commands

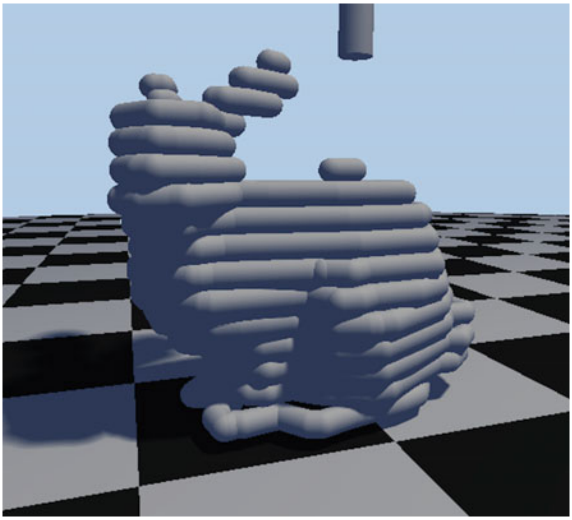

Fig. 2 Complex geometries: a simplified version of the stanford bunny

3.2 Case 2: A More Complex Geometry

The second component is a simplified Stanford bunny, see Fig. 2. It has been scaled down so that the nozzle size is relatively large compared to the part. This is a much more complex model, and there is significant slow down compared to the previous case. Despite this it is still possible to interact with the model during the simulation by lowering the resolution.

3.3 Case 3: Additive and Subtractive Combination

The final case highlights the flexibility of using signed distance fields to represent geometry and Boolean set operations to combine them. Figure 3 shows how by using this technique it is easy to combine both additive and subtractive manufacturing processes into one simulation. The cutting tool shape can be changed just like it is possible to change the deposition shape.

3.4 Discussion and Limitations

The system presented in this paper simulates manufacturing processes by combining distance field primitives together using CSG operations. This is a very powerful method and closely mimics the intuitive physical process of adding or subtracting material to produce a part. The result is a form of in-process geometry

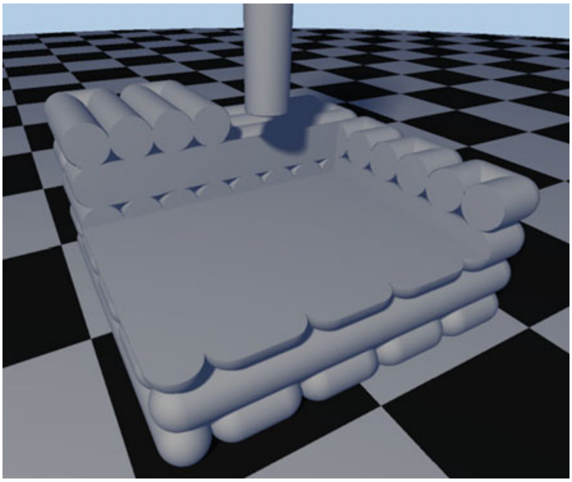

Fig. 3 Additive and subtractive combination: a hybrid manufacturing simulation approach

that could be used as an input to a number of different models, such as finite element analyses.

The rendering system has some major limitations in its current incarnation. This simulation method does not discretise or sample the geometry. This ensures that there is no loss of fidelity with subsequent operations and as such the accuracy of the displayed result is only limited by the resolution selected within the renderer. The problem with this is that the CSG-tree ends up being repeatedly evaluated at every iteration; a very time consuming process. The simplest way to manage the complexity of distance field modelling is to discretise the workspace and store data inside voxel grids for visualisation. Uniform voxel grids require a high resolution to capture small details, but applying a high resolution grid to the whole model is inefficient and requires lots of memory. The use of hierarchical organisation techniques [14] or bounding volumes [15] is popular to try and limit these inefficiencies. These limit the distance function evaluations to those within an area close to the point being queried, drastically reducing the overall number of evaluations. This is definitely an area for improvement in the future.

4 Conclusions

Implicit geometric representations have many benefits over using explicit boundary representations or polygonal meshes. The primary benefit comes from the distance calculation inherent within the definition of the geometry. This makes it easy to perform Boolean set operations, such as unions, intersections, and differences. These operations can be combined to simulate AM deposition and traditional subtractive processes such as machining.

Ray-marching distance fields for visualisation purposes is fast and lends itself well to the parallel processing capabilities of graphics hardware and the processing pipeline. This enables complex simulations to be run at an interactive frame rate, with the ability to move around the virtual part to investigate its geometrical properties. One caveat is that evaluating the CSG-tree each iteration to find distances can quickly become a problem with more complex geometries. In this case, some form of sampling of hierarchical organisation is required.

Within these experiments the deposition shape has been represented by a capsule shape. This is a simple approximation to the shape produced by extruding material from a nozzle (as in fused deposition modelling). An investigation into deposition shapes from different AM technologies would be an interesting direction to explore in the future.

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Part VI
Invited Session 2: Sustainability and Resilience in Agri-food Supply Chains

Agri-food Supply Chain for Mitigation of Volatilities in the Role of Intermediary: A Case Study of a Mushroom Trading Company in Taiwan

Tzu-Yen Huang and Luisa Huaccho Huatuco

Abstract The agri-food industry in Taiwan is facing many challenges, e.g. low level of food self-sufficiency due to small scale lands and ageing farmers, natural disasters accelerated by climate change. A case study of a mushroom trading company in Taiwan is presented. Face-to face semi-structured interviews, collection of company's documents and field observations were carried out to study the volatilities from the supply side, demand side, macro environment and structural problems. The unpredictable changes or risks that cause the volatilities in agri-food supply chain are identified, also their effects on the company's performance. Finally, some recommendations are provided to the company for developing a better strategy for mitigating the effects of such volatilities.

Keywords Agri-food supply chains · Volatility · Intermediary · Case study

1 Introduction

This study focuses on the role of intermediaries because in agri-food supply chains, they make their profit by addressing the gap between farmers and retailers. This position makes them easily vulnerable to both upstream and downstream volatilities. The research question addressed in this paper is: *To what extent do volatilities in agri-food supply chains affect the role of intermediary companies*?

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2 Literature Review

Volatility is defined in the Oxford Dictionary as the feature of "*changing rapidly and unpredictably*". As the market has expanded globally, volatility becomes an important problem for supply chain management. New studies have begun to explore the factors of volatility in agro-food supply chains focusing on three types: commodity price, yields of commodity and volatility of farmers' incomes [1]. The volatility will cause uncertainty and low stock, which reduces willingness to invest [2]. A Supply Chain Volatility Index was proposed defining volatility as the turbulent business environment that forces actors to build a more flexible supply chain structure [3]. In agri-food supply chains, volatility is caused by various factors from upstream to downstream. The volatility of price is affected by production and consumption shocks [4]. According to the economic theory of demand, the changing demand is caused by the price of: products, substitutes, consumer income, socioeconomic, demographic factors [5] and social networks [6]. In reference to the demographic aspect, the effect of rapidly developing countries, such as China and other Asian countries has fostered the demand of food [7]. This trend affects suppliers who have to modify their packaging, including information, such as: nutrition ingredients and cooking instructions, allowing suppliers to value consumer services [8]. Generally, the weather is considered an important factor that yields volatility [4]. Climate has been regarded as the main factor affecting the income volatility of farmers [1]. However, other studies [9] hold the opposing view that they thought weather shocks have small influence on price volatility. Inputs, such as animal feed, energy, fertilizers and transportation costs can also transmit volatility to the prices of products [10]. The agricultural market is usually fragmented because the policy and general market behavior with price are inconsistent [11]. The failure of EU and USA agro-fuel policies was one of the factors that led to the severe global food crisis in 2008 [12]. The policies usually aim to solve the problems. However, they need accurate prediction and estimations; otherwise, the results will become worse and make the situation more complicated. The restrictions could amplify price volatility in international markets [13]. The following strategies to mitigate the potential losses due to supply chain volatility have been cited in the literature: agility, collaboration, diversification and information sharing. Retailers in food supply chains have the biggest market power and are seen as the gatekeepers between producers and consumers [14]. Some middlemen tend to reduce the costs from upstream participants of supply chains or facilitate corrupt transactions [15]; namely, farmers in agri-food supply chain are in the most vulnerable status. Therefore, critics claimed that intermediaries should be ruled out. The role of middlemen is determined by the economic value for their partners [16]. The role of middlemen is to reduce the time-spending in searching for partners when outsourcing is needed [17], but the explanation is not complete [18]. Generally, the reasons that middlemen are needed in the market are the existence of uncertainty and mismatch between supply and demand with complex and non-standardized

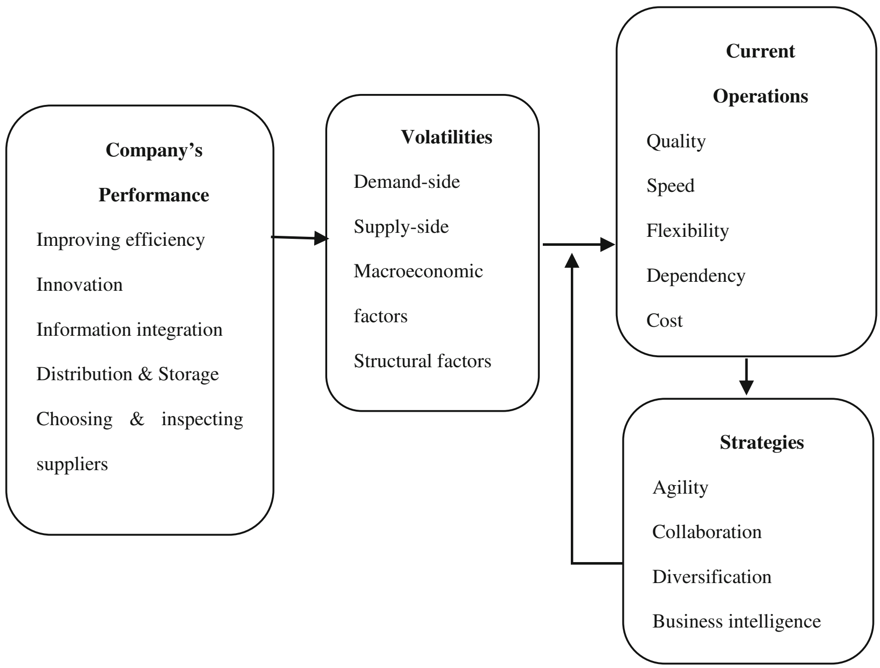

Fig. 1 Conceptual model of the study

products, capability of buyers and perishability of products are hard to control [19]. The conceptual model for the study in this paper based on the literature review is provided in Fig. 1.

3 Methodology

A case study will be carried out at Company A. Data will be collected by face-to-face semi-structured interviews. Due to the language difference between the interviews (in Chinese) and the presentation of the study (in English), the task of translating the questionnaire is important to avoid misunderstanding of questions. The duration of the interviews will be between 30 and 60 min each, depending on the amount of related information each interviewee can provide. Interviewees will invite managers from different departments, due to the different responsibilities and job contents in the company. For complementing the contents of interviews, observations plus documents will be provided by the company. Moreover, secondary data about the mushroom industry in Taiwan will be collected from government publishing, market research and other reliable sources will be used to support the interviewees' perspectives in this study. For validity, the questionnaire used in the semi-structured interviews was designed based on relevant literature review. The purpose was to understand if the company had encountered problems, such as the volatilities of price, climate or policy. Additionally, some questions on the strategies to improve the company's agility, information sharing, etc. were also included. For reliability, this study used the triangulation method whereby different data sources are taken into account, e.g. semi-structured interviews (with multiple respondents), real-life observations of the company's operations and analysis of secondary data.

4 Findings and Analysis of Results

The company started by trading two types of mushrooms in 1970s; and gradually expanded its business and products. At present, the company has 42 employees, nine departments and 150 cooperative farms. Table 1 presents the profile of the interviewees' details. Figure 2 represents Company A's supply chain.

Table 1 The information of interviewees

Job title	Duration	Location	Themes
Executive of brand	1 h 51 min	Office in University of Asia in Taiwan	Company's structure and operations Volatilities and relevant challenges The conducted strategies for volatilities
Sales director	1 h 7 min	Company A	Same as the above plus the way of cooperation with customers
Head of cultivation	21 min	Office in one of the farms	Same as above plus the way of cooperation with suppliers

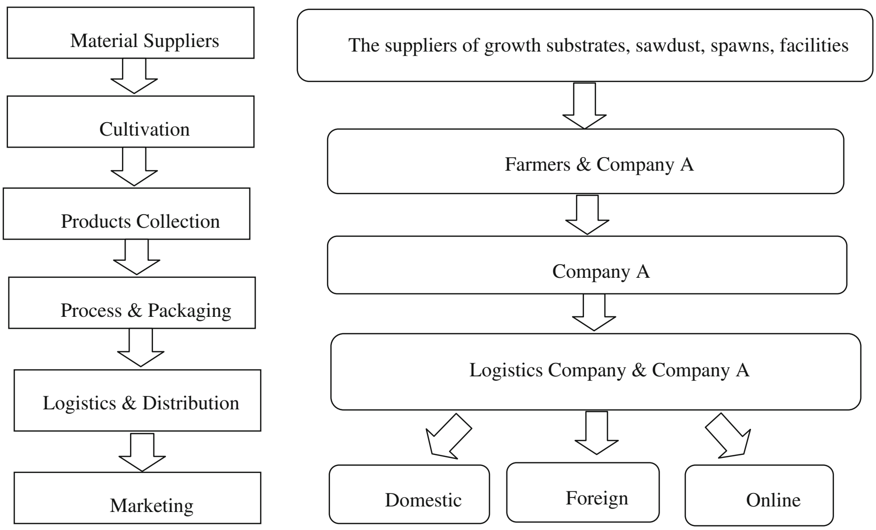

Fig. 2 Company A's supply chain

4.1 Demand-Side Factors

Due to the large bargaining power of some retailers, Company A and its suppliers are subject to some unreasonable demand. The Sales Director gave two examples to explain the situation, "*The big retailers, such as Costco and RT-Mart, can order ten boxes of mushroom today, but 100 boxes tomorrow,*" and Company A cannot control the demand; also, it has small power to negotiate the crucial customer. He said, the other example is, "*Once supermarket Y holds a promotion of a specific mushroom, it will cause the shortage of the product, which also affects other customers.*" Likewise, Y is a big customer that contributes to the amount of sales of Company A. Company A can only try its best to meet Y's demand. When the large-scale customers raise the unpredictable requests to Company A, which might suffer the sudden shortage of stock and danger the relationships with other customers.

4.2 Supply-Side Factors

First, the Sales Director mentioned that although weather is one of the factors leading to volatility, the influence is limited because most mushrooms are cultivated indoors and under controlled facilities. Only minor species, such as *shiitake* are cultivated in traditional way and affected by weather changes. The quality will be affected after natural disaster. "*Because we are in the middle status, if customer receives the products with poor quality, they will blame it on us. Although we did the quality inspection, some of the poor products still would be missed,*" (Sales Director) Company A's reputation will be damaged by the upstream supply. Second, according to the Head of Cultivation, in order to harvest quality products, the good production environment needs to be maintained at a particular temperature. If the facilities are not appropriate, the temperature might deviate and affect the quality. Although automatic production can avoid labor issues, the cost of facilities is high and needs regular maintenance. In addition, with the poor facilities of some suppliers, Company A cannot provide the products with consistent quality, so customers might search for other suppliers.

4.3 Macroeconomic Factors

More agreements have been signed since Taiwan joined the World Trade Organization (WTO) in 2001. Afterwards, the Economic Cooperation Framework Agreement (ECFA) was reached with China in 2010 for further liberalization of trade. The agreements aim to reduce the obstacles of trade between countries; therefore, the implementation of free or low tariff becomes a challenge for the relevant industry. For example, Chinese farmers have advantages of cheap labor, land and resources that Taiwanese farmers cannot compete with, because Taiwanese farmers are small-scale and cannot benefit from economies of scale; therefore, their production cost is higher than foreign farmers. These policies inevitably lead to many objections; however, the new Trans-Pacific Partnership (TPP), which dramatically reduces the obstacles of tariff and flows of labor and commodity will be signed up next year. In the mushroom industry, dried *Shiitake* and *Flammulina* are included in the free tariff product in agreement, but with restricted volume. The Executive of Brand said, "*Although the government protects the agri-food industry from threat of foreign products, once the government opens the market, the structure of industry must be changed.*" This shows that the policy could resist the temporary changes of global agreements, but in the long-term, the agri-food industry have to prepare for globalization.

4.4 Structural Factors

Following from the previous point on the changes of policy from centralization to open markets, this will have also implications in the structural factors too, as new ways of trading and players in the supply chain are expected to emerge. First, the Executive of Brand said that the problem that members in Company A's supply chain partners have little knowledge about each other. For example, Company A's customers will ask the clear-cut size of mushroom; however, suppliers have difficulty in controlling the size and the thickness of each mushroom. Second, the cooperation with farmers in most agricultural industry are verbal contracts, which do not have official binding. The Executive of Brand said, "*Once the market price rises, the cooperative farmers may sell the products by themselves secretly.*" If Company A's customers find out there are the other channels for consumers to gain the same product, Company A will be questioned about selling the product to their rivals. However, the second strategy—lease contracts may solve this problem. The content of contracts is having appointment with farmers that Company A will buy the arranged volume. The method can mitigate farmers' volatile income for sustainable production. But the contracts are only oral agreement that the volatility of farmers' uncontrollable activities such as misstating the production cannot be avoided. Third, strategic alliances are conducted by the Company A that includes cooperation with university, beverage stores and food stores to increase the diversity of products. The Executive of Brand said, "*When you upgrade the agri-food into processed product, the price is set according to the value rather than its cost.*" It means the processed products have higher value in the market.

5 Discussion of Results

This paper addressed the research question: *To what extent do volatilities in agri-food supply chain affect the role of intermediary companies*? Volatilities mean the members in supply chain cannot have accurate planning for production and purchasing. Because Company A has large power by collecting large amount of mushroom from small-scale farmers in Taiwan [20], it can negotiate the fair transactional conditions with its powerful partners for sharing the loss from volatilities equally and helping farmers to sell the redundant products. First, volatilities in the agri-food supply chains have several factors in this case. However, comparing with the literature review, the important factor—weather [1] does not affect the fluctuated income for Company A. Since the feature of production environment for mushroom is indoors and can be controlled by automatic facilities. In addition, the cost of inputs, such as materials, electricity and facilities indeed leads to the unstable profits. Third, the macroeconomic factors have a small influence on volatile supply chain because the government policies still tend to protect the vulnerable agricultural industry currently. Fourth, in terms of the problem of volume amplification [21], the farmers need 3–4 months to cultivate mushrooms. The volume is decided before production no matter how the demand changes. According to the literature, one of strategy consists of agility that emphasizing flexibility and speed [22].

6 Conclusions

Company A encounters the volatilities from supply side, demand side, macro environment and structural factors that have different degrees of influence for the company's operations. The intermediary was observed as the necessary role to mitigate the volatilities in the mushroom supply chain because of the middle status to promote the farmers improvement and having the contract with farmers to protect them from volatile purchasing prices. Company A keeps struggling to mitigate the volatilities in supply chain by its marketing and negotiation capabilities. A limitation is that the case study methodology cannot provide generalized results, and are only relevant to the participant company. Some quantitative measures of volatility on operations performance according to different mitigation strategies could be added in future research.

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Exploring Dynamic Natural-Resource-Based Capabilities for Sustainable Agri-food Chains

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Abstract The natural-resource-based-view (NRBV) is positively presented in literature as a competitive approach to sustainable operations. In spite of this the theory has struggled to transition into industry; something which academics attribute to a lack of practical guidance and ill-defined capabilities. The purpose this study is to identify NRBV capabilities. This is done via review of seminal NRBV studies and exploration of a synergistic relationship with SSCM, permitting the identification of potentially relevant capabilities. Dynamic capabilities theory is then applied to categorize the capabilities and further enhance applicability. A qualitative multiple-interview methodological approach is employed to empirically investigate the capabilities within the context of the Scottish agri-food sector.

Keywords Natural resource based view · Sustainable supply chain management · Dynamic capabilities

1 Introduction

Conceived of twenty years ago [1] the natural resource based view (NRBV) resonates strongly with today's markets [2] and still features prominently in modern literature [3]. The NRBV attempts to address issues of ecological and societal degradation via four symbiotic resources that render competitive benefits for the firm with regards to cost, quality, efficiency and differentiation [1, 4]. However, in spite of a strong literary following and academic praise [3, 5–7] the theory is victim

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to one major criticism: a lack of practical applicability [8]. In the most part this is attributed to insufficient academic attention as to the capabilities required to support NRBV resources [4], conflicting the intrinsic nature of resources and capabilities [9]. Thus, via extensive literature review and empirical investigation we present a framework to guide the practical realization on the NRBV.

The construction of a conceptual capability framework is derived from three literary fields, which are discussed in some detail in this paper. Firstly seminal NRBV studies are reviewed, highlighting a number of implications for possible capabilities. Secondly the NRBV's synergistic relationship with sustainable supply chain management (SSCM) [3] is explored, permitting the identification and capabilities which may be of relevance to the NRBV. Finally, dynamic capabilities are used to categorize capabilities into activities of sensing, seizing and transforming [10] in accordance with the widely accepted argument that resource based theories lack applicability without dynamic capabilities [4, 11, 12]. A qualitative multiple-interview methodological approach is then employed explore the framework within the context of the Scottish agri-food sector, resulting in an empirically enforced definition of NRBV capabilities. The following research objectives are set:

- Identify NRBV capabilities from a review of seminal studies;
- explore the synergistic topic of SSCM to draw out additional capabilities;
- categorizing these capabilities according to dynamic capabilities create a conceptual framework;
- and assess and refine the framework via empirical investigation of the agri-food sector.

2 Literature Review

2.1 The Natural-Resource-Based View

The NRBV traditionally consisted of three symbiotic resources, namely pollution prevention, product stewardship and sustainable development, and emerged in response to the realization that sustainable operations may offer competitive advantage [1]. Whilst pollution prevention exists as the dominant resource [5, 6], closely followed by product stewardship [2], sustainable development suffered considerable neglect and misinterpretation [4, 12] resulting in a subsequent division into clean technologies [13] and base of the pyramid (BoP) [14]. Given the desire to ease issues of inapplicability this study is inclusive of pollution prevention, product stewardship, clean technologies and BoP, in what we term the 'four resource perspective'.

Pollution prevention supports the minimization of waste and emissions in internal production and is presented as a strategy of great significance in modern business [15]. By shifting waste management from control towards prevention firms are expected to benefit from improved efficiency and productivity and reduced costs [1, 5]. In its initial conception pollution prevention capabilities, aside from environmental management systems (EMS), are entirely neglected. A later review of the topic offers greater insight, highlighting employee skills and participation, organizational commitment, cross-functional integration, technology, human resource management and political acumen as pollution prevention capabilities [5]. More recently, continuous improvement is defined as the resource's fundamental capability [4, 15–17].

Product stewardship offers advancement for pollution prevention [13] in that it extends the prioritization of the natural throughout the entire product lifecycle rather than just within the firm [1]. From this perspective the natural environment is a key stakeholder, and firms are expected to benefit economically and environmentally via the creation of wholly sustainable products and processes [1, 12]. With regards to capabilities an emphasis is placed on cross-functional management, stakeholder management, and lifecycle analysis [1]. The significance of lifecycle analysis has since been reinforced [3, 16], but it is certainly notable that product stewardship capabilities have not been awarded the same attention as those of pollution prevention.

Clean technologies offers a further advancement of both pollution prevention and product stewardship, in that whilst pollution prevention and product stewardship aim to reduce impact or realize zero impact operations, clean technologies works towards positive impact operations [4]. More specifically, it is argued that companies must be receptive to future technologies [13], encouraging a shift away from traditional routines and processes and calling for the creative redesign of industries to support sustainability [18]. With regards to capabilities entrepreneurial capabilities, organizational vision and future positioning and commercialization capabilities [4, 18] are emphasized. Political acumen is also linked with clean technologies [19].

BoP can be presented as the socially focused counterpart of sustainable development. It focuses upon the alleviation of social ills via stimulation of economic growth in and support of emerging markets [14]. BoP in its simplest form argues that engaging in business at the bottom of the pyramid may ease poverty whilst simultaneously increasing profits by targeting previously neglected and unsaturated markets [18]. For this to succeed products and services may need to be specifically designed to suit unfamiliar needs [14]. As such capabilities such as technological innovation [20], external collaboration [20], entrepreneurship and the radical modification of business models and processes [21] are linked with BoP.

2.2 NRBV Extensions and Developments

The prominence of the NRBV in academia has resulted in several attempts at theoretical extension and development. The first comes from Aragon-Correa and Sharma [6] in which a contingent proactive environmental strategy in presented to assist the realization of pollution prevention. Their paper argues the need for a proactive approach to the environment in pollution prevention, and pertinently highlights stakeholder integration, continuous improvement, higher order shared learning, the interpretation of environmental issues as opportunities, and the reconfiguration and recombination of resources as the necessary capabilities to support such an approach. A second attempt comes from Mencug and Ozanne [8] and their natural environment orientation which aims to add approachability to pollution prevention, product stewardship and Hart's original sustainable development. Their paper presents corporate social responsibility inspired measurements to pollution prevention; proactive management, risk-taking and entrepreneurship to product stewardship; and internal reporting, environmental audits and reviews, internal environmental rewards and employee training to sustainable development. The third attempt comes from Shi et al. [2] and builds upon links between green supply chain management (GSCM) and pollution prevention and product stewardship to create the NRB-GSCM model [2]. The model links pollution prevention with environmental policy, consideration of environmental criteria, process optimization, internal environmental management procedures and advanced prevention and safety methods. Product stewardship is linked with green purchasing, green distribution and design for the environment.

2.3 The NRBV and SSCM

There exist notable links between the NRBV and supply chain management throughout literature [3, 4, 12]. Whilst this has already manifested in the NRB-GSCM model [2], we propose an amalgamation with SSCM on account its inclusion of both ecological and social principles which corresponds with our four resource perspective of the NRBV. In addition, SSCM's widespread industry acceptance and application [12] may offer some resolve to the NRBV's issues of practical inapplicability and managerial avoidance.

Pollution prevention and SSCM can be linked easily via their paralleled intentions of waste management, encouraging existing studies to consider the role of environmental management systems and lean [22] in pollution prevention. Links between product stewardship and SSCM are already noted to some extent in the NRB-GSCM model in which green purchasing, green distribution and design for the environment are prioritized [2], but synergies have also been noted with regards to supply chain collaboration [17], leading to consideration of capabilities such as stakeholder integration, inter-organizational learning and joint sustainable innovation. Clean technologies has been compared with SSCM's environmental technologies [23] rendering consideration supply chain aptitude for new technologies, employee training and technological management systems. Closed-loop SCM [12, 18], corporate environmental responsibility [24] and resource efficient supply chains [7] have also been linked with clean technologies. BoP corresponds with discussion of socially responsible SCM [24] and SCM in developing economies [7], rendering consideration of capabilities such as supplier training and capacity building, shared culture, exploitation of external opportunities and strategic market entry. Links with external collaboration also warrant consideration of social embeddedness and joint planning for societal objectives [20].

2.4 The NRBV and Dynamic Capabilities

It is commonly argued resource-based theories lack adaptability [11] and that in order to avoid irrelevance or invalidity in turbulent markets resources must continuously evolve [25]. Teece's dynamic capabilities emerged in response to this, encouraging firms to adapt to rapidly changing environments via the continuous development of organizational competencies [26]. Dynamic capabilities were well received in literature, and have been credited with overcoming one of the major flaws on the NRBV [4, 6]. This said they are in their own right criticized for lacking practical applicability for failing to offer specific definition of a dynamic capability [6]. Resolving this in a later paper, Teece argues that dynamic capabilities cannot be defined and should not be seen as an 'add on' to the NRBV [10]. Instead, dynamic capabilities, which are divided into categories of sensing, seizing and transforming activities, should be used to describe and guide NRBV capabilities. Given the purpose of this study is to guide NRBV application this is a philosophy to which we conform (Table 1).

Table 1 Dynamic natural-resource-based capabilties for SSCM

	Sensing (seek and shape opportunities)	Seizing (implementing and managing new opportunities)	Transforming (organizational evolution)
PP	– Employee awareness [5] – Political acumen [5] – Proactive approach to the environment [6, 8] – Stakeholder integration [6] – Higher order shared learning [6] – Consideration of environmental criteria	– EMS [1, 22] – Employee skills [5] – Technological knowhow [5] – Resource reconfiguration/ management [6] – Performance measurement [8] – Environmental policy [2] – Internal environmental management procedures [2]	– Continuous improvement [4, 6, 15–17] – Organizational commitment [5] – Cross functional integration [5] – Human resource management [5] – Process optimization [2] – Advanced prevention and safety methods [2] – Lean [22]

(continued)

Table 1 (continued)

	Sensing (seek and shape opportunities)	Seizing (implementing and managing new opportunities)	Transforming (organizational evolution)
PS	– Stakeholder integration [1] – Lifecycle analysis [1, 3, 16] – Risk taking [8] – Proactive approach to the environment [8] – Inter-organizational learning [17]	– Collaborative supply chain relationships [1, 17] – Cross functional management [1] – Green purchasing [2] – Green distribution [2] – Reverse logistics [12]	– Stakeholder management [1] – Long term (lifecycle) perspective [1] – Design for the environment [2] – Joint sustainable innovation [17]
CT	– Organizational vision [4, 18] – Political acumen [19] – Environmental audits [7, 8] – Rewards for environmental ideas [8]	– Aptitude for new technologies [4, 23] – Commercialization [4, 18] – Internal reporting [8] – Employee training [8, 23] – Technological management systems [23] – Closed loop supply chain management [12]	– Creative redesign of industries [18] – Future positioning [4, 18] – Corporate environmental responsibility [24]
BoP	– External collaboration [20] – Environmental audits [8] – Internal rewards for environmental ideas [8] – Joint planning for social objectives [20]	– Technological innovation [20] – Development of new business models and processes [21] – Internal and external reporting [8] – Employee and supplier training [7, 8]	– Aptitude for radical change [21] – Integration [20] – Shared culture [7, 24] – Capacity building [7, 24]

PP Pollution Prevention; *PS* Product Stewardship; *CT* Clean Technologies; *BoP* Base of the Pyramid

3 Research Design

Adopting a deductive approach, the framework is then empirically tested via a two-stage qualitative methodological approach. The first stage being exploratory analysis of the Scottish agri-food sector involving both primary and secondary data, and the second stage being multiple in-depth, semi structured interviews with purposefully selected Scottish agri-food companies. The Scottish agri-food sector was selected as a result of its high investment in sustainability [27], its prioritization of sustainability as a source of competitiveness [27] and its heavy reliance on natural resources [28].

Exploratory analysis of the Scottish agri-food sector began with the collection and review of secondary data from media, NGO and company websites and recent government policy and legislation. The purpose of this was to assess the extent to which each of the NRBV's four resources assumed relevance throughout the sector via identification of any NRBV traits. Alongside analysis of secondary data we also conducted eight telephone interviews during our exploratory analysis. These took place with Scottish agri-food companies who demonstrated particularly strong interests in sustainability. Avoiding the use of any NRBV or SSCM terminologies, companies are asked to discuss and describe their approach to and experiences of sustainability. This acted as a pilot study and facilitated the identification and inclusion of additional capabilities, namely vertical integration, ISO 14001 and family-based principles.

To complete the study multiple in-depth, semi-structured interviews are undertaken with Scottish agri-food companies. The purpose of this is to facilitate the empirical reinforcement or rejection of the NRBV capabilities drawn out from literature. Companies are purposefully selected according to their operations' resemblance to the NRBV. More specifically, we approached companies who promoted use of strategies comparable to pollution prevention, product stewardship clean technologies and BoP. Naturally chosen companies require a strong relationship with sustainability, and as such we were particularly drawn to companies who had won awards related to sustainability or who had patented sustainable technologies or systems. Along with their presence in the Scottish agri-food sector, such characteristics acted as our only criteria, and we did not select based upon size, turnover or sub-sector. It is hoped that this will assist in an accurate representation of the Scottish agri-food sector, or rather a realistic agri-food chain. Interviews are semi-structured in the hope of facilitating a conversational approach to data collection in which the respondent is encouraged to lead the discussion. In doing so respondents are asked about their experiences of and approached to sustainability, allowing any supportive capabilities to emerge without bias or leading. In addition an observation approach is employed via the tour of company premises, in which again the respondent is encouraged to take control and highlight any operations of facilities which they feel support sustainability. Interviews typically last between 90 and 120 min and are recorded and later transcribed. The intention is to match strategies discussed during interviews to one of the four NRBV resources and then to identify which capabilities were linked with those strategies. To this point six interviews have taken place, the details of which can be seen in Table 2.

Table 2 Participant details

Company	Description	Turnover	Employees	Person(s) interviewed
1	Potato grower/producer	£175 million	850	Environmental energy efficiency officer
2	Potato grower	£180 million	900	Growing manager and agronomist
3	Potato breeders	£4 million	15	Chief executive
4	Dairy farmer/ice-cream producer	£11 million	70	Marketing director and finance director
5	Seaweed harvester and producer	£200,000	10	CEO, marketing executive
6	Potato growers	£2.5 million	10	CEO and environmental officer

4 Preliminary Findings

The results of the exploratory analysis suggest that all four of Hart's NRBV resources are employed in the Scottish agri-food sector, albeit in varying degrees. In line with the intended diffusion of the NRBV [13] and recent review of the theory [4] pollution prevention emerges as the dominant resource, followed by product stewardship, then clean technologies, and then BoP. Whilst BoP could easily be identified in secondary data, it only featured in three of the eight exploratory phone interviews, and pertinently on a local rather than global level in some conflict to BoP's original conception [18]. Notably this corresponds with a recent review of the topic [21] in which it is suggested that that BoP exists predominantly in local communities. Pertinently, throughout discussion of such strategies, all eight companies referenced competitive benefits with particular emphasis on cost saving, and all eight companies relied heavily on supply chain terminologies to explain their approach to sustainability.

Whilst it is too early to definitively confirm or reject any of the capabilities drawn out from the literature review or exploratory analysis, preliminarily results of the interviews do imply strong correspondence. Every pollution prevention capability, with the exception of human resource management, features at some point throughout the six interviews. In addition, frequent discussion of ISO 14001 and company's specifically designed EMS throughout interviews add definition to the more obscure terms of EMS and internal environmental policy. Every product stewardship capability can be identified in interview transcripts, and in particular stakeholder integration, inter-organizational learning and joint sustainable innovation feature prominently. In five of the six companies interviews respondents link this with supermarket led auditing systems, certification and participation in online forums, whilst four companies link it with government funding for collaborative projects. Discussion of green purchasing, distribution and reverse logistics invites further discussion of certification along with technologies such as free cooling and electronic tracking and carbon measurement. With the exception of commercialization, technological management systems and the creative redesign of industries, clean technology capabilities also demonstrate consistency between literature review and empirical findings. Closed loop supply chain management emerges with particular significance, whilst additional capabilities such as leadership and organizational creativity warrant discussion. Pertinently, as with the exploratory analysis, family principles and heritage emerge with significance with four of the companies claiming their ability to look beyond short term investments and for the sake of the next generation permitted the creation or adoption of clean technologies. Finally, BoP capabilities, with the exception of capacity building, feature in the interviews, albeit this is again on a local rather than global scale. In the most part such discussions include references to support of local charities, on site animal and wildlife conservation projects and lobbying for local causes. As such external collaboration, joint planning for social objectives and shared culture assume dominance, whilst family principles and heritage again emerge with relevance (Table 3).

Table 3 Preliminary Results

	Sensing	Seizing	Transforming
PP	– Employee awareness – Political acumen – Proactive approach to the environment – Stakeholder integration – Shared learning – Consideration of environmental criteria	– Purpose built EMS – Employee skills – Technological know how – Resource management – Performance measurement – ISO 14001	– Continuous improvement – Organizational commitment – Cross functional integration – Process optimization – Advanced safety methods – Lean
PS	– Stakeholder integration – Inter-organizational learning – Participation in online forums – Lifecycle analysis – Risk taking – Proactive approach	– Collaborative supply chain relationships – Vertical integration – Green purchasing – Distribution/logistic technologies – Government funding – Carbon measurement	– Joint sustainable innovation – Stakeholder management – Certification – Design for the environment – Relationship with supermarket
CT	– Organizational vision – Political acumen – Environmental audits – Internal environmental rewards – Organizational creativity	– Aptitude for technologies – Internal reporting – Employee training – Closed loop supply chains – Leadership – Family management	– Future positioning – Corporate environmental responsibility – Long term perspective – Detachment from short term financial returns
BoP	– External collaboration – Environmental audits – Internal environmental rewards – Joint planning for social objectives	– Technological innovation – Internal and external reporting – Employee/supplier training – Family management	– Aptitude for radical change – Integration – Shared culture – Long term perspective

PP Pollution Prevention; *PS* Product Stewardship; *CT* Clean Technologies; *BoP* Base of the Pyramid

5 Conclusions

Although research is yet to be completed, preliminary results appear positive and support the value of this study. High levels of consistency between the conceptual framework of dynamic natural resource based capabilities and empirical analysis suggests that the amalgamation of the NRBV, SSCM and dynamic capabilities is logical and offers a long overdue guide to the adoption and management of competitive and sustainable operations. Whilst this is of course the principle aim of this study, several contributions are sought: first to refine twenty years of NRBV and related literature; secondly to respond to calls for the definition of supportive NRBV capabilities [4]; and thirdly to support the continued development of sustainable operations in the Scottish agri-food sector.

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Supplier Selection Processes: A Case Study in a Chinese Dairy Company

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Abstract This research studies the supplier selection process in a company in the Chinese Dairy Industry. The literature review includes the food supply chain, the frameworks and models of supplier selection, the selection methods and sourcing strategies. A case study methodology including seven interviews with managers and employees was carried out. This paper discusses the similarities and differences between the research findings and literature review. It suggests the company extends the time period of the field trips to visit its potential suppliers, in order to obtain sufficient and reliable information for conducting supplier selection processes.

Keywords Supplier selection process · Case study · Chinese dairy company

1 Introduction

The main research question addressed in this paper is: *How is the supplier selection process carried out in the Chinese dairy industry*? The Chinese dairy industry has a huge potential market for dairy consumption [1]. Since 2000, there has been an average 12.8 % annual growth of dairy production and consumption, and it is expected that Chinese dairy consumption would increase to 38 % by 2022. However, after the melamine scandal in 2008, consumers are more concerned about the quality of supply of the dairy products. This makes the dairy companies ensure that the selected suppliers can supply high-quality raw materials [2]. The case study company is a well-known Chinese dairy company that provides outstanding high-quality dairy products.

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2 Literature Review

Supplier selection processes (SSPs) involve both qualitative and quantitative factors, which need to be considered when selecting suppliers [3]. Supplier selection strategies are regarded as one of the strategic operating choices in the company [4]. Purchasers must choose and apply an appropriate method to select the best suppliers for the company [5]. In the long run, the SSP is beneficial to improve the company's overall performance [6]. The strategic sourcing process includes six steps: Assess Opportunities, Profile Internally and Externally, Develop the Sourcing Strategy, Screen Suppliers and Create Selection Criteria, Conduct Supplier Selection, Negotiate and Implement Agreements [6]. In developing the sourcing strategy stage, Kralijc's model [7] classified the supplies into four quadrants according to their complexity/risk impact and value potential, namely: bottleneck, critical, routine and leverage. The framework of SSP includes four steps: problem definition, formulation of criteria, qualification and final choice [7]. This is useful for the buyers to understand the purchasing situation and requirements. As a result, the buyers can make sure the final selected supplier can meet all their requirements [8]. It is important to determine and set up the supplier evaluation criteria based on companies' own situation [9]. Dickson [10] identified 23 supplier selection criteria according to a survey of hundreds purchasing managers. The top five criteria according to this study are: quality, delivery, performance history, warranties and claim policies, production facilities and capacity [11]. Weber et al. [12] indicate that quality, net price, delivery, production facilities and capabilities, technical capabilities, financial position and performance are ranked as the most important criteria for supplier selection. They state that supplier selection criteria is a multi-process, and the ranking or priority of the criteria can be changed according to the different procurement situations [12]. Ellram [13] asserts that the qualitative criteria are important for the company to build up long-term relationships with its suppliers. These qualitative criteria can be divided into four categories: financial issues, organizational culture and strategy, technology issues and other factors, such as safety, business references and supplier's customer base. Furthermore, these factors can help the companies achieve supplier alignment and positive cooperative relationships in the long run [14]. Birch [15] indicates that it is essential that the buyers need to negotiate and make the agreement with its suppliers firstly, and then decide the most important criteria. In this study, the criteria can be divided into five types: cost, logistics, quality, development and management [15]. As it can be seen 'quality' is the most commonly cited criteria, and that price/cost plays a less prominent role. Supplier selection decision-making methods and techniques can be divided into three types: Multi-criteria Decision Making (MCDM), Mathematical Programming (MP) and Artificial Intelligence (AI) techniques [16]. According to Chai et al. [16], the most frequently used MCDM technique is Analytical Hierarchy Process Method (AHP), followed by MP technique: linear programming (LP) and

AI technique: Genetic Algorithm (GA). The relevant techniques and methods for this research are explained next. In the Linear weighting method, weights are given to each criterion by highest and least importance. The scores are given subjectively and heavily rely on purchaser's experience and ability, buyers discuss ratings with other department members, and then determine the overall scores for each supplier by assessing the suppliers' performance. As a result, the supplier with the highest overall scores will be selected [17]. AHP is a useful method that can be applied together with Linear Weighting Models. AHP method will firstly decompose the complex problem in a form of hierarchy in order to identify each level's criteria and sub-criteria. Then all the criteria are combined together and the weights are given to derive the final research outcomes. This model is widely used by the companies in supplier selection, since it considers and measures both quantitative and qualitative criteria [6].

3 Research Methodology

The research uses a single case study for understanding the SSP in a company in the Chinese dairy industry. The main data collection method used in this research is remote semi-structured interviews. In terms of validity, the interview questions are based on the literature review. In addition, they were looked through and checked by two colleagues. Therefore, they were able to measure and explore the research question. To ensure research reliability, the roles of the selected interviewees are all related to the research topic and have worked in the Company for more than five years. The selected interviewed managers and employees are knowledgeable and have rich working experience. In China, mail questionnaires often cause ineffective response, and Chinese management is relative inexperienced with research surveys [18]. Therefore, the data are mainly collected by semi-structured interviews on SSP in the company and visiting its website. It is necessary to consider the trade-offs between the efficiency and richness of data, and make the collected data valuable and deep enough [19]. The interviews include Company's Operations Manager, Purchasing Manager, Supply Chain Manager and four employees in the Purchasing department. Each interview's duration will be approximately one hour, and the interviews are mainly conducted by Skype and telephone. The direction of the interviews are: the company's current sourced raw materials for dairy products, whether the company has spent analysis before sourcing, whether the company has purchasing portfolio analysis, the company's routine, critical, bottleneck and leverage products, general SSP of the company, detailed information about each stage of SSP in the company, the company's supplier selection criteria, how the company conducts the supplier selection and negotiates with the suppliers, are there any problems existing in the company's current SSP?

4 Analysis of Research Results

The case study company is a Chinese dairy Company, established in 1987 and located in Heze city, Shandong Province in China. The average annual sales of the company is RMB 200 million (£20 million approximately), and it has more than 1000 employees. The company's current dairy products are shown in Table 1.

The raw materials for producing cold and UHT dairy products are different. More information is collected during the interviews with Purchasing and Supply Chain Managers and it will be described in the following sections. According to the interview with Supply Chain Manager, the outlook of the company's supply chain is shown in Fig. 1.

The Purchasing Manager provided detailed information of the raw materials from suppliers (see Table 2).

"*Unlike other industries, in terms of food industry, we need to be concerned more about food safety issues. That means we need to control the product quality in the initial stage of the supply chain. Therefore, the Company regards SSP as a very important part in the operations. The SSP of the company can be mainly divided into seven stages*." (Purchasing Manager.) First, the company needs to understand what kind of supplies they are looking for. Second, the company conducts spend analysis. The spend analysis is conducted by choosing at least five potential suppliers in order to have an overview of the quality, cost, service and delivery information of the purchased items. Third, understanding the buying situation and

Table 1 Company's main dairy products

Main categories	Product lines
Cold dairy products (short storage life)	Pasteurized milk
	Fruity cold milk
	Yogurt
Ultra-high temperature treated (UHT) dairy products (longer storage life)	Organic milk
	UHT fruity and vegetable milk

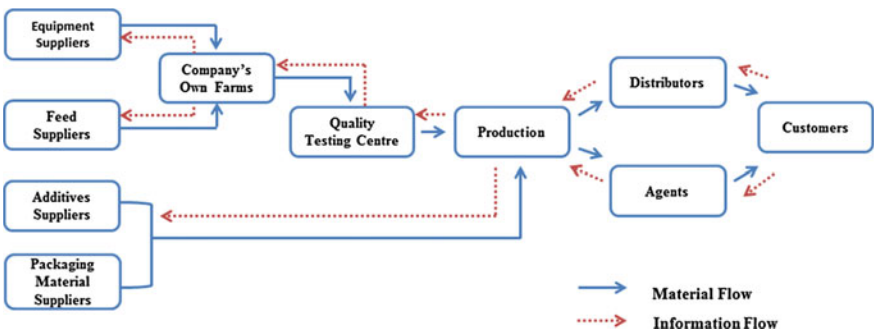

Fig. 1 Outlook of the supply chain

Table 2 Main raw materials from suppliers

Main raw materials supplied from outside of the company	Main items included
Feed raw materials	Alfalfa
	Guinea grass
	Corns
Additives raw materials	Sweeteners
	Fruity flavors
	Stabilizer
Equipment supplies	Milk station: feeding machines, cooling and storage machines (in each farm)
	Factory: processing machines
Packaging materials	Bottled packaging
	Tetra pak packaging
	Bag packaging

identifying the sourcing strategy for each supplied item. In order to identify the sourcing strategies, the company mainly considers two factors: the supply risk and the profit impact, which is the same as Kraljic's [7] purchasing portfolio analysis. Fourth, by using AHP method to decompose the complex sourcing requirements into different hierarchical levels [20, 21]. After setting up the criteria, the weighted of importance will be given to each criteria. The weights are determined by the purchasing department. Fifth, searching suppliers and obtaining suppliers' information. Sixth, screening potential suppliers, using the established criteria and selecting method to sort the most suitable suppliers, i.e. Linear Weighted Method. The scoring process is normally conducted by three people, the Purchasing Manager and two employees in the purchasing department. The given scores are multiplied with the weighted importance to get the final scores. Finally, the supplier with the highest score is selected. Last but not least, after selecting the best supplier, the company will negotiate and sign the contracts. As shown in Fig. 2, according to Kraljic [7] Portfolio Analysis, the Purchasing Manager indicates that the four main raw materials can be divided into Routine and Critical quadrants.

Feeding, Packaging and Additives materials, are regarded as Routine items, since they have low supply risk and low profit impact. They can be sourced from a large number of suppliers. The profit impact of these kinds of raw materials is low as well; the expenses of sourcing these will not affect the profit of the company. "*The sourcing strategy for the Routine items are followed the Purchasing strategy based on efficiency, which is focusing on sourcing from the most efficient suppliers and lowering the costs at a maximum level* (*whilst maintaining the same level of quality, delivery,* etc.)." (Purchasing Manager.) The equipment supplies are regarded as critical items, because they have relative high supply risk and high profit impact to the company. "*The sourcing strategy for the Critical items is based on cooperation. In terms of the equipment supplies, it has the relative high supply risk and it can have a high profit impact to the company.*" (Purchasing Manager.)

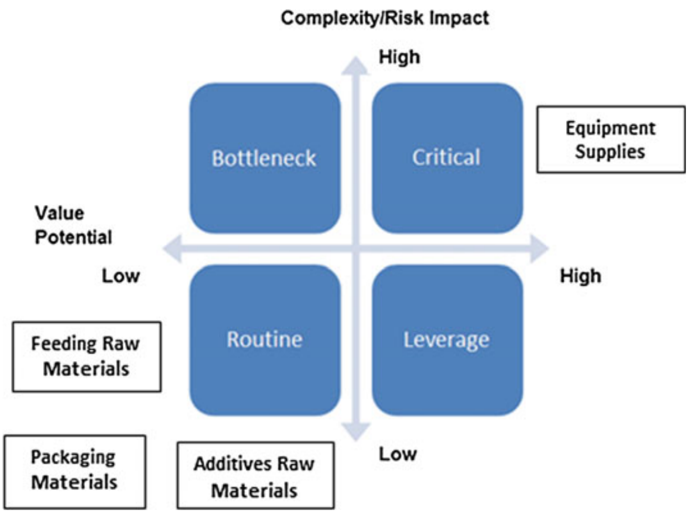

Fig. 2 The purchasing portfolio analysis of the dairy products

Therefore, in terms of the critical items, the company needs to pay more attention to building long-term relationship with these suppliers. The Company considers quality, cost, delivery, economic of scales and company culture when selecting suppliers. However, in different sourcing situations, the ranking of the criteria is different. Firstly, the company uses the AHP method, which decomposes its complex requirements into different hierarchical levels. Then, the Company sets up the criteria for each hierarchical level and combines them together at the end. Figure 3 shows the supplier selection criteria of the company.

A descriptive matrix can be used for data display, its rows and columns can display different aspects of collected data [22]. See Table 3.

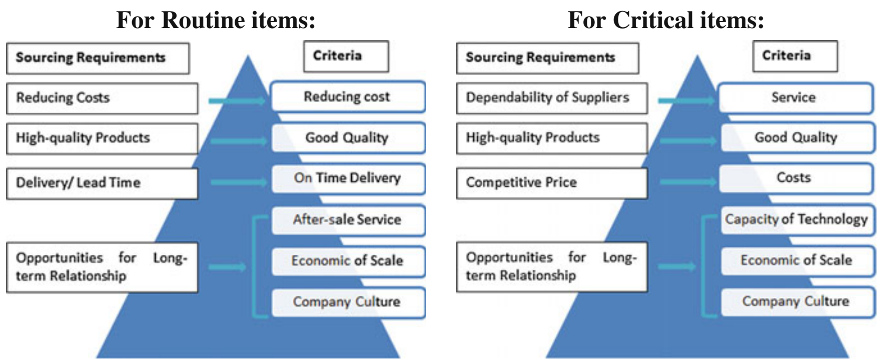

Fig. 3 Supplier selection criteria in different hierarchy levels

Table 3 Summarized information of the interviews

Role of interviewee	Interview topic	Key answers
Operations manager	General information about the company and sustainability	Description of the product lines
Supply Chain manager	Outlook of supply chain and sustainable procurement	Outlook of the supply chain; related strategies in the supply chain
Purchasing manager	SSP and criteria sustainable procurement	Description of raw materials; seven-step SSP; different selection criteria on different sourcing strategies; sourcing strategies of different raw materials
Employee 1	Supplier selection criteria and existing problems	Supplier selection criteria are different according to different sourcing strategies; the main existing problem is limited time period of field trips and insufficient collected data for supplier selection
Employee 2		
Employee 3		Lack of policies to penalize the supplier who created quality problems
Employee 4		

5 Discussion

This research addressed the research question: *How is the supplier selection process carried out in the Chinese dairy industry*? The company uses spend analysis, Kraljic's [7] purchasing portfolio analysis, AHP method and Linear weighted method during the SSPs. The supplier selection criteria combines SSP [6] and Junior et al.'s [8] framework of supplier selection. It combines these two frameworks together and sets up its own SSPs. The Purchasing Manager and the employees usually carry out business trips to visit potential suppliers, but these appear too short to capture their true quality potential. The Purchasing Department could extend the period of business trips.

6 Conclusions

This research explored the SSPs at a company in the Chinese dairy industry. The company combines different models, and sets up its own selection processes model. The limitation of this research is conducting a single case study. The results cannot be generalized to other dairy companies. In terms of the further research, the quantitative analysis of the company's preferred AHP criteria could be studied.

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Supply Chain Risk Management Identification and Mitigation: A Case Study in a Chinese Dairy Company

Canglong Yu and Luisa Huaccho Huatuco

Abstract This study explores the risks management in the dairy supply chain in China. Using a single case study methodology, semi-structured interviews with different supply chain experts working in the dairy company were conducted. Through the interviews, data was gathered about the supply chain network of the dairy company, managers' understanding of supply chain risks management, and risks inherent in the dairy supply chain. In general, the company has the awareness of supply chain risks and it has created an 'organic economy business model' which reflects its concept of supply chain risk management. However, at the operational level, the company does not have any supply chain risks management program. By following the Failure Mode Effect Analysis (FMEA) framework, the risks identified in the supply chain have been assessed and prioritized. Some recommendations have been given to mitigate the high priority risks.

Keywords Supply chain · Risk management · Food industry · Case study · Failure mode effect analysis (FMEA)

1 Introduction

Supply chain risk management has become critical because of the increasing uncertainty in today's marketplace. Many frameworks have been proposed as a systematic approach to manage the supply chain risks. By comparing several risk identification and management frameworks/tools, the Failure Mode Effect Analysis (FMEA) is selected and used in this research. In the Chinese dairy industry, after the melamine scandal in 2008, the Chinese government introduced a number of

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policies to encourage the development of modern, standardized and scaled farms in order to produce high quality raw milk. The development of dairy industry has some problems in China, which can seriously impact on the quality of raw milk, the milk production and distribution; with consequences, such as cost increase, decreased sales and vulnerable supply chains. The main research question addressed in this paper is: *What are the supply chain risks inherent to a Chinese dairy supply chain and how can they be identified and mitigated*?

2 Literature Review

Supply chain risk management identifies the potential sources of risk, and evaluates the possible consequences and takes appropriate actions [1]. It has received increased attention in managing product safety and security in industries where product safety and security is critical, such as food, pharmaceuticals, and automobiles [2]. The risk management process is important to be controlled in a dairy supply chain, as the recent milk contamination scandals have exposed its vulnerabilities. The main sources of risk in a dairy supply chain are: quality of milking animal, feeding availability, milking handling practices, milk bulking practices and milk transportation [3]. The most agreed supply chain management process consists of five steps: risk identification, risk assessment and evaluation, risk mitigation, implementation and action, and risk monitoring and continuously improving [4].

2.1 Risk Identification

This step provides decision makers with comprehensive understanding of the variety and interrelationships of supply chain risks and the potential consequences [5]. See Table 1 for some popular techniques and frameworks used in the phase of risk identification.

Table 1 Factors considered when selecting frameworks/techniques

	SCM	Checklists	FTA	FMEA	CEA	SCOR
Risk identification (qualitative risk)	X	X	X	X	X	X
Risk assessment (quantifying risk)			X	X		
Potential effects of failure				X		
Action plan				X		

Note SCM Supply Chain Mapping, *FTA* Fault Tree Analysis, *CEA* Ishikawa Cause and Effect Analysis, *SCOR* Supply Chain Operations Reference

2.2 Risk Assessment and Evaluation

This step involves the determination of the consequences the severity level, risk ranking, and risk acceptance [5]. The effects of risks can be categorized into three types, namely 'time-based', 'finance-based', and 'quality-based' [6, p. 590]. Based on the principle of as low as reasonably practicable, the risks can be defined as acceptable, tolerable and unacceptable. The level is set up by the cross-functional team of the organization to ensure appropriate criteria are used [5].

2.3 Risk Mitigation

The response to risks should at least ensure that the supply chain continues working, uses resources and capabilities efficiently, and complies with regulations and laws [7]. In responding to risks, there are many strategies that can be adopted by the organization including increasing collaboration with partners, increasing system flexibility, and building buffers at critical nodes across the supply chain [8]. Risks can be mitigated through supplier collaboration, customer collaboration, and internal collaboration [9]. The level of integration has positive impact on the supply chain agility that is regarded as a capacity to respond rapidly to changes and disruptions [10]. However, the complexity of a food supply chain could make the information exchange and sharing inefficient, hindering supply chain collaboration. The level of the economic size, structure and access on ICT application is another important barriers for achieving high level of supply chain collaboration [12]. The company can mitigate supply chain risks by achieving supply chain flexibility [3]. The more efficient strategies for mitigating risks focus on supply chain flexibility rather than on redundancy [13].

2.4 Implementation and Risk Monitoring

The last two steps are implementation of the risk mitigation strategies, and continuous monitoring and improvement. The monitoring program should be taken in place in order to examine the progress are according to the plan, and take corrective actions if there is deviation from the desired performance. FMEA is widely used to identify potential failures within a system, and to evaluate their effects by ranking their severity, occurrence and detection [14]. The stages of conducting FMEA analysis are: identify risk categories, identify potential risks, score Severity, Occurrence, and Detection for each risk, calculate the Risk Priority Number (RPN) and Risk Score Value (RSV) for each risk, analyze risk and decide if the risk is acceptable, develop actions to mitigate risks where needed, reassess the risks with another cycle of FMEA [15].

3 Methodology

The research methodology used is case study to explore the phenomenon in its natural context [16]. The case research in operation management is different from case study in the field of social sciences, while in operations management, the research design should pay more attention on the studied processes or system of the operation. The methods of data collection are from the processes or system [17]. Data collection methods used in case study usually includes documentary analysis, interviews and observation [18]. This study will use semi-structured interviews as primary data collection method plus document analysis and the company's website as secondary data. In the phase of data collection, the researcher needs to consider the trade-offs between efficiency and data reliability [17]. Chinese language will be used in the interviews and the data will be translated back to English by the researcher and presented in the section of research findings. Given the distance between UK and China, and time issues, the interviews will be conducted via Skype. The duration of each interview will last 1.5 h approximately. The semi-structured interviews will cover the following themes: Supply chain in the dairy company, Risk management program in the company, Risks associated with supply side, demand side, internal operation and control, environmental side.

4 Analysis of Results

The case study organization is a large Chinese dairy company in the North of China. The company was founded in 1987. It has 1000 employees and achieved £20 million sales in 2014. The company has a good reputation in the Chinese dairy industry and it prides itself for striving towards providing high-quality dairy products. According to data collected from supply chain manager, operations manager, purchasing manager, and sales manager, the supply chain structure of the company is illustrated as Fig. 1.

The company has two main dairy product groups, which are cold dairy products and UHT milk (Ultra-high temperature treated). Table 2 presents the key data collected during the interviews. The focus on efficiency rather than effectiveness and trend of outsourcing are two factors making the supply chain more vulnerable and exposed to disruption, risks [19].

4.1 Supply Risk

Supply risks is usually associated with the supplier evaluation, selection and performance management. [5]. "*One of the key criteria for testing the quality of DDGS is the level of Aspergillum flavus in the product. The DDGS is the waste of grains*

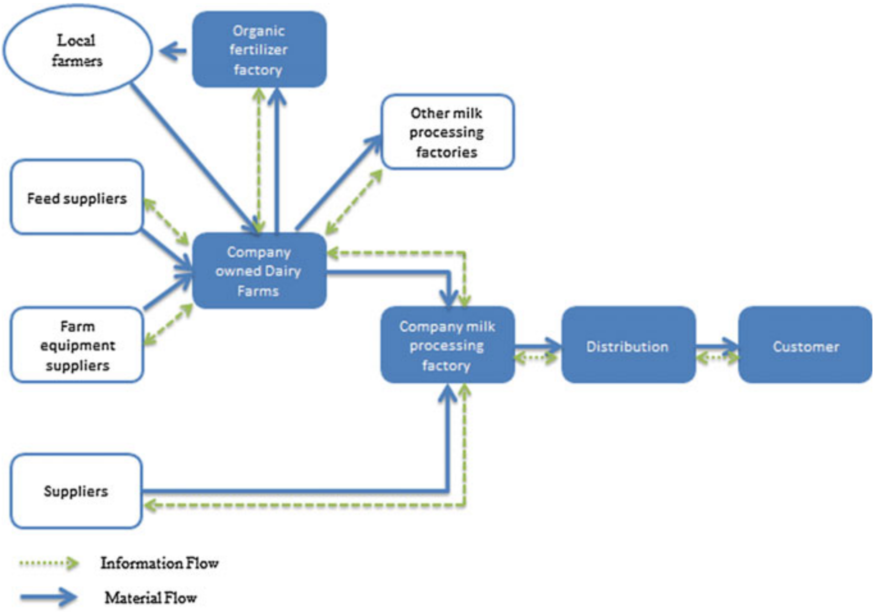

Fig. 1 Supply chain structure of the dairy company

after fermenting. The level of Aspergillum flavus can be different from batches. If the cows are feed with DDGS containing high level of aspergillum flavus, the raw milk will also have high level of aspergillum flavus." (Purchasing manager.) The risks related to the purchase price for materials have positive influence on the organizational business continuity and economic sustainability. The farming equipment and milk processing equipment usually involves with a large amount of money and requires a good level of after-sales service and technical supports from supplier. Supplier capabilities in regard to design, technology development, and problem solving have direct influence on the operational performance of the focal firm [20]. In summary, the supply risks inherent in the supply chain of dairy company can be summarized as the quality of DDGS, the price of *leymus chinensis*, supplier capabilities, and supplier financial stress.

4.2 Demand Risk

Demand risks are uncertainties emerging from downstream of supply chain that could disrupt the company supply. As the information provided by the sales manager the demand risks are mainly from two aspects. The first aspect of demand risk is for the raw milk. The price of raw milk in the market is largely depending on the relationship of supply and demand. When the supply is more than demand,

Table 2 Illustration of key data for supply chain risks in the dairy company

Interview topics	Job title	Key answers
Supply chain risk management awareness	Operations manager	It has awareness of supply chain risks, and has created its unique business model
	Supply chain manager	It vertically integrates its supply chain by internalizing business dairy farming, organic fertilizer, milk processing, and marketing
	Purchasing manager	It would develop a better relationship with suppliers in order to make cooperation smooth, but no periodical supplier audit or evaluation program in the company
	Sales manager	In the demand side, it does not only sell raw milk to other milk processors, but has its own branding of dairy product as well, but at the operational level, the company does not do anything to manage the demand risks
Supply risks	Operations manager	Limited supplier capabilities to solving technique problems of milking station, supplier bankruptcy and their financial stress
	Supply chain manager	Price of *leymus chinensis*, quality of DDGS (key feed ingredient for cows)
	Purchasing manager	Quality of DDGS, Supplier delivery
Demand risks	Operations manager	Price fluctuation of raw milk in the market, demand fluctuation of dairy product in consumer market
	Sales manager	
Operational and control risks	Operations manager	Cold chain performance, milk processing line down, the governance of product development of the company, security management of dairy farms
	Supply chain manager	Company's IT system, cold chain performance
	Purchasing manager	Company's IT system
Environmental risks	Operations manager	Droughts, policies and regulations change
	Supply chain manager	

the price of raw milk is low. In the worst case, the selling price could be same as the cost of producing the raw milk. This has a big impact on the overall profit of the company. Another aspect of risks in the demand side is the demand fluctuation for the dairy products in the consumer market. As said by the sales manager: "*The main driving force of demand fluctuation is the weather. Although the fluctuation of demand is relatively easy to predict, however, you cannot ask cows to adjust their productivity of raw milk in order to meet the change of demand in the consumer market.*" (Sales manager.) In summary, the main risks are the price fluctuation of raw milk and the demand fluctuation of dairy products in the consumer market.

4.3 Operational and Control Risk

Operational risk is defined as "*the risk of loss resulting from inadequate or failed internal processes, people, and systems or from external events*" [21, p. 225]. The risks may rise from internal process or from the interactions with external partners. Control risks are usually associated with the application or implementation of rules, policies, systems or procedures that govern the operational process. The cold chain of the company does not perform well. Due to the under-developed cold logistics facilities, such as the efficiency of cold warehousing, the limited number of refrigerated trucks, over long-distance, milk cannot be stored more than two days when they are sold or delivered at customer, or even worse. The milk processing line down is another risk that inherent in the day-to-day operations. According to the operations manager, the milk processing involves about ten steps from raw milk to the final packaging. Any mistake or operational errors in any single step could cause the whole processing line down. The IT system is one of operational risks admitted by the purchasing manager and supply chain manager. In the process of product design and development, risks can arise [9]. The operations manager provides an example of product development issues caused by the internal governance structure. This can be referred as control risk. In the farming aspect, the operations manager says that the security management of dairy farms is one of the risks inherent in the daily farming operation. The management of personnel and vehicle access to the farms, the regular health check of cows, the construction structure of cattle facilities can be potential risks causing cattle disease, zoonotic diseases, cattle hurt. In summary, the main operational risks are the use of IT system, cold chain performance and milk processing line. Product development process and security management of dairy farms are the risks of control. It is worth mentioning that in food supply chains production is pushed rather than pulled by demand [22].

4.4 Environmental Risk

Examples of environmental risks are natural disaster, social-political issues, technological development, regulation or policy changes. The environmental risks that inherent in the dairy company supply chain are shown below as given by the operations manager: "*This area is very stable in terms of natural disasters, but the drought in summer occurs quite often although it is not extreme. It could impact on the productivity of corns of local framers. This can have influence on the price and quantity of corns we purchase from local market.*" (Operations manager.) Policy and regulation change is another aspect of environmental risks which can impact on the firm's supply chain. This was confirmed by the supply chain manager. "*The government is paying more attention on the environmental issues. Laws and policies in regarding the environment improvements have been published.*

This could impact on how the business is running in terms of dealing with pollution." (Supply chain manager.) In summary, the drought in summer is a repeating pattern risk that can impact on the business of the dairy company. In addition, the policies and regulations changes in terms of environmental issues and food safety issues may have influence on the company supply chain as well.

4.5 Risk Assessment

The principle of assessing risks of FMEA framework is valuing the risks in terms of impact level, the probability of occurrence, and the risk detecting level with current methods or process. Table 3 shows the rating scale used in the research from the interviews. Table 4 shows the risks identified inherent in the company supply chain.

The next step after calculating the RPN and RSV for each risk is to figure out the critical RPN and RSV. There are no scientific rules in selecting critical values [22]. The principle of Pareto analysis is described as the 80:20 rule, it means that 80 % of outcomes are from 20 % of causes.

By using the Pareto principle, the critical RPN is set as 160 and critical RSV is set as 40. Figure 2 shows the scatter diagram of identified risks. The risks fall in the section in which RPN and RSV values are higher than critical values are defined as the high risks of which actions need to be taken to mitigate such risks. Those risks are: the quality of DDGS, price fluctuation of raw milk, cold chain performance, and milk processing line down. Those risks are categorized as the supply risk, demand risk and operation risk.

5 Discussion

This paper addressed the research question: *What are the supply chain risks inherent in a Chinese dairy supply chain and how can they be identified and mitigated*? The company has awareness of managing supply chain risks and it has created and developed a unique organic economy business model 'from land to

Table 3 Rating scale of severity, occurrence and detection

Rating scale/severity and occurrence	Degree	Rating scale/detection level	Degree
9–10	Very high	10	Detection is not possible
7–9	High	7–9	Low
4–6	Moderate	4–6	Moderate
2–3	Low	3–4	High
1	Minor	1–2	Very high

Table 4 List of supply chain risks identified in the dairy company supply chain

Risk Source	Potential failure	Severity (S)	Occurrence (O)	Detection (D)	S * O = RSV	S * O * D = RPN
Supply	Quality of DDGS	8	6	4	48	192
	The price of *leymus chinensis*	5	6	6	30	180
	Supplier capabilities	5	2	8	10	50
	Supplier financial stress	9	2	7	18	126
Demand	Cold chain performance	6	7	4	42	168
	Price fluctuation of raw milk	7	7	4	49	196
	Demand fluctuation in consumer market	7	4	5	28	140
Operations and control	Milk processing line down	8	5	4	40	160
	IT system	6	3	5	18	90
	Product development process	8	3	7	24	168
	Security management of dairy farms	8	2	3	16	48
Environment	Drought of local weather	7	4	5	28	140
	Policy and regulation changes	8	2	5	16	80

Note RSV Risk Score Value, *RPN* Risk Priority Number

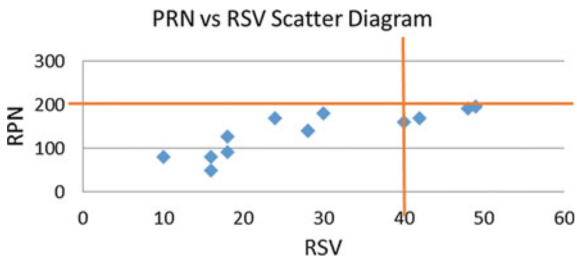

Fig. 2 Scatter diagram of identified risks

table', it vertically collaborates and integrates its supply chain. Its strategy for managing risks is quite similar to what has been studied by different researchers, which is through supply chain collaboration to mitigate supply chain risks and achieve resilient supply chain [9, 12]. The level of information sharing and visibility has an impact on the level of supply chain collaboration [12]. In managing the poor quality of supplied goods, better planning and coordination with suppliers, dual-sourcing, flexible capacity, supplier development program are proposed as mitigation strategies [24]. In China, the development of Guanxi ("relationship") with supplier can reduce opportunism and decrease transaction costs [19]. It also helps the organization build trust with suppliers. Given the characteristics of the DDGS this is fast-moving with low demand uncertainty; decentralized approach of building specialized capacity is suggested for managing such items [24]. The company can build certain level of inventory to cover the risks of stock-outs when the quality of supplied goods is not accepted. In managing the demand risk, the company can mitigate the risk of demand volatile trough the cost reduction in operations [25]. It can improve the effectiveness and efficiency of farming to further reduce the farming cost. Flexibility is a form of pooling strategy. It is often used to manage the day-to-day recurrent risks [24].

6 Conclusions

The implications of this study are: it rises awareness of risk management in the operational level for the company, it provides the company with a framework of risk management, it identified 13 risks in the dairy supply chain and it provides recommendations for mitigating the risks (high RPN and RSV values). Nevertheless, there are some limitations. The first limitation is the lack of generalizability. As the paper only studies a single company in the dairy industry, the findings are not universal. The second limitation is the remote nature of data collection. As the data were collected through Skype interviews, the researchers cannot capture the body language of the interviewees. This could limit the understanding of the contents. Given the limitations of the research, it provides room for further study in the field of supply chain risks in dairy industry in China. Quantitative data could be also collected through surveys, and be further analyzed with the qualitative data collected through more case studies.

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Future Prospects of Sustainable Aquaculture Supply Chain Practices

G. Malindretos, I. Vlachos, I. Manikas and M. Chatzimanolakis

Abstract Interest in sustainable supply chains has been rapidly growing for over a decade with an increased pressure to all parties of the agrifood supply chains to deal effectively with food safety and quality issues as well as minimize social and environmental impact. Aquaculture is a neglected research area, although it is recognized as one of the most promising, though also controversial new industries. This paper utilizes a single-case study, action research to examine how sustainability can be promoted on operational level. More specifically, the study analyses a project developed by one of the biggest companies in the Mediterranean, concerning the strategic supply chain re-design towards reducing lead times from production to consumption. The impressive improvements in terms of lead time and cost savings and the conclusions and recommendations drawn in this study are expected to reveal the direction for further research towards integration of aquaculture development with the sustainability imperatives.

Keywords Sustainable aquaculture · Fish farming · Fishery supply chain · Freshness · Value stream mapping

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1 Introduction

The issue of Sustainable Aquaculture supply chain practices belongs to the broader scope of sustainable supply chain management (SSCM) which has been rapidly growing in the last 25 years towards becoming mainstream in the agenda, at the level of companies, governments and different social partners. It is also related, in particular, with the issue of food safety and quality, which has utmost importance to consumers, especially after a series of toxigenic food crises (mad cow disease, genetically modified food, chickens and pigs with dioxins, etc.), towards affecting eating habits and demand for certified products. In this context, there has been an increased pressure in the supply chain and more particularly in the agrifood sector to deal with quality, social and environmental issues.

It is required more so in the aquaculture, as research and practice has followed well behind the above mentioned trends, though it has started to be recognized as one of the most promising, though yet controversial new industries. This study becomes therefore especially important, in view of the expected rise in the fisheries and aquaculture share in global supply up to 2030, projected to supply over 60 % of fish destined for direct human consumption, according to World Bank. Moreover, many advocates believe that aquaculture has the potential in resolving serious environmental, health and food supply problems.

The first part of the paper addresses different methods and frameworks for sustainability performance evaluation, as the sector is increasingly challenged by emerging issues which require innovative actions to address the economic, social, environmental and governance aspects.

In the second part, the paper presents a project developed by the biggest company in Mediterranean fish farming, Nireus Aquaculture S.A. More specifically, it analyses the steps of strategic supply chain re-design of the Nireus chain which has involved significant infrastructure investments and reengineering operations.

2 The Aquaculture Sector Development

A relatively not sufficiently appreciated, yet promising, fact is that fish can play major role in satisfying the world's growing middle income group needs, while also meeting the food security needs of the poorest. Nowadays more than 800 million people in the world continue suffering from chronic malnourishment, while global population is expected to grow by another 2 billion to reach 9.6 billion people by 2050. It has been seen as a "daunting challenge", engaging researchers, technical experts, management and leadership.

Aquaculture has grown at impressive rates over the past three decades. More specifically world aquaculture production volume increased at an average rate of 8.6 % per year, including inland aquaculture and mariculture. World foodfish aquaculture production more than doubled from 32.4 million tonnes in 2000 to 66.6 million tonnes in 2012 [1]. FAO estimates that world food fish aquaculture production rose by 5.8 % to 70.5 million tonnes in 2013, with production of farmed aquatic plants (including mostly seaweeds) being estimated at 26.1 million tonnes. The global trend of aquaculture development gaining importance in total fish supply has remained uninterrupted. Farmed food fish contributed a record 42.2 % of the total 158 million tonnes of fish produced by capture fisheries (including for non food uses) and aquaculture in 2012. This compares with just 13.4 % in 1990 and 25.7 % in 2000. As a consequence of these trends, the aquaculture's contribution to total food fish supply grew from 9 % in 1980 to 48 % in 2011. The estimated number of fish farmers also grew from 3.9 million in 1990 to 16.6 million in 2010. This has contributed in keeping fish food price relatively low and make seafood more accessible to consumers around the world. In addition, fish is highly traded in international markets, since about 200 countries reported exports of fish and fishery products in 2012, implying inherent imbalances in international trade and a mechanism to resolve such imbalances [2–4].

3 Sustainability in the Aquaculture Sector: Main Concerns

This literature review makes a brief reference of main studies and aspects concerning the post-war development of the aquaculture sector in the context of the continuing knowledge process towards the sustainability goals.

The environmental impacts of aquaculture have invited increasing work by academics. Indicatively, an interesting study ten years ago focused upon nutrition from fish in Mediterranean compared with the environment charging [5]. Among the most noticeable conclusions that have been drawn were that the waste discharge is less than 5 % of the total anthropogenic discharge to environment and climate charges.

The main topics of discussion are associated though with global fish stocks, namely the depletion of wild seed stocks and the reduction of genetic variability of wild populations. More broadly there has been extensive attention of relevant international organizations about aquaculture development. Thus, in particular, the International Food Policy Research Institute (IFPRI), the FAO, the University of Arkansas at Pine Bluff and the World Bank have formed a so-called "IMPACT model" (from the originals of "International Model for Policy of Agricultural Commodities and Trade") [6]. This report offers a global view of fish supply and demand. Based on trends in each country or group of countries for the production of capture fisheries and aquaculture and those for the consumption of fish, driven by income and population growth, this model simulates outcomes of interactions across countries and regions and makes projections of global fish supply and demand into 2030. This work built on the publication Fish to 2020 by Delgado and others [7]. Furthermore, linking with an ecosystem model could allow to address a much wider range of policy-relevant questions by combining questions of trade and agricultural policy with questions of environmental management and technology adoption in fisheries [6].

In addition, a collective study of Mediterranean aquaculture, the AQUAMED, was more recently carried out [8]. A set of top-five research activities was recommended for the Research Agenda:

1. Set up of a group of economic interest involving Industry, Research, Policy Makers
2. New alternative sources of material to replace fish meal and fish oil in aquafeed composition
3. Communication and marketing strategies
4. Simplification of administrative process (time, costs, burden) for licensing collection and harmonization of laws and procedures
5. Support to the territorial planning and to the identification of allocated zones for aquaculture.

4 Fishery Supply Chains and Consumers Awareness

One of the effects of globalization is the rapid transformation of the corporate world to lend greater importance to supply chain management. In the last decade, it has become a key tool in improving operational efficiency worldwide, as it rationalizes product development cycles, increases product diversity, improves quality and customer satisfaction and responds to customer demands.

The length of the supply chain can also vary depending on the product and country of origin and final destination of a product. Usually the shorter the distance from producer to consumer, the more transparent the supply chain [9]. However smoking, salting or canning extends the fish supply chain even when the destination of the product is local.

Supply chains must always be aligned with consumers' expectations and needs. Quality attributes like freshness, nutrition and health benefits are of top concern in the consumers' fish food purchasing criteria list, as shown in Fig. 1. The more fresh is the "fish" the higher value it has: a rule of fish price devaluation is that "every day that fish remains unsold the average selling price decreases by at least 20 %".

In addition, 79 % state that environmental considerations are more important than price when purchasing seafood. However, a crucial issue limiting the uptake of sustainably sourced products is the importance given to sustainability issues by consumers, when compared to other factors that determine purchase. Today, whilst 40 % of consumers in Europe say they are willing to pay between 5 and 10 % more for sustainable seafood, only 25 % would pay a price premium greater than 10 % [10].

Media reports on threatened fish species (such as bluefin tuna, and North Sea cod) in European waters have led to a growing awareness by European consumers about the sustainability of fish products. In Europe, sustainability awareness about the fisheries sector is more prominent among central (including, amongst others, Poland, Slovakia and Slovenia) and northern European countries including the UK, Scandinavian countries, Germany and Switzerland. The latter boasted in 2006 the

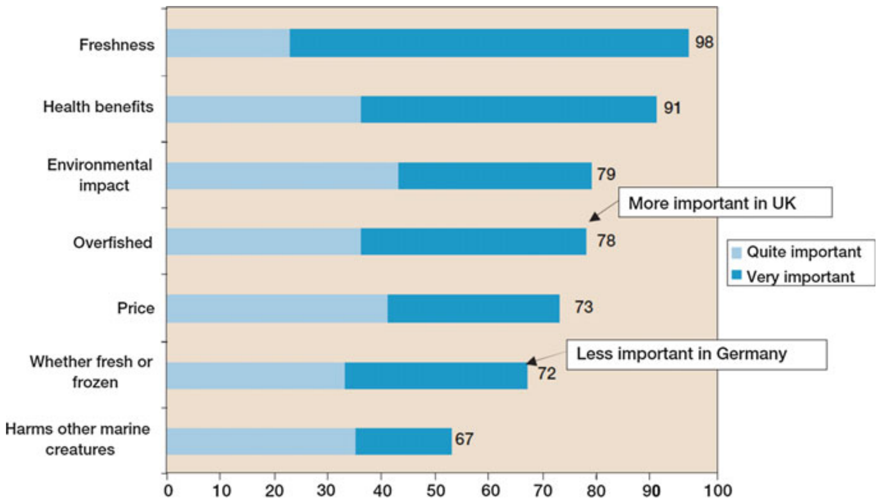


Fig. 1 Importance of specific seafood attributes to consumers. *Source* Seafood Choices Alliance [10]

highest number of MSC certified brands in the market place. According to a Seafood Choices Alliance public opinion poll [10], on average 85 % of consumers in the UK, Germany and Spain expressed a great concern about the current state of the world's oceans.

An interesting fact related to consumer awareness of sustainable seafood options is that sustainability is couched in terms of species population and not the general health of the ecosystem. There seems to be large-scale consumer awareness on sustainability issues such as the over-fishing and the killing of non-targeted species (such as dolphins and turtles). However, there is significantly less awareness of the interrelation of species in an ecosystem and the cascading effect that one species can have on others, or the impact of aquaculture on the environment and the use of drugs and chemicals in aquaculture.

Consumers need clearer and more reliable information on the sustainability of seafood—this will have an impact on their purchasing decisions: 86 % say they would be more likely to buy seafood labelled as environmentally responsible [11].

Although there are still important challenges in terms of transparency, information sharing and traceability, several large retailers are working on their policies and implementation.

5 Popular Tools for Assessing Sustainability

As far as the future of fish population concerns, efforts aim at quantifying the variability in management systems around the world to evaluate which particular attributes lead to more successful outcomes for fish populations and fisheries [12].

Moreover, recently developed Fishery Performance Indicators (FPI) can be used for rapid assessment of fisheries that are not formally assessed [13].

In terms of environmental aspects, there is a trend of increasing use of the "life cycle assessment" (LCA) in the aquaculture supply. This methodology aims at evaluating the environmental performance of a product over the full product life cycle and analyze all the environmental effects at integrated a product supply chain level. Some important models that have been also developed internationally for the sustainability goal, are the Dashboard of Sustainability [14], the Sustainability Assessment Model [15], the ABCD four steps method [16].

Lean techniques and tools aim also at minimizing non-value adding processes which are characterized by "wastes" of different forms. According to Emiliani and Stec [17] these include overproduction, waiting, transportation, processing, inventories, moving (both operator and machine) and defects. Value Stream Mapping (VSM), a key tool of Lean thinking, is a visual representation of processes, aiming at identifying non-value-adding activities, as an opportunity to eliminate waste through problem solving.

6 Supply Chain Re-engineering Towards Sustainability: The Nireus Aquaculture S.A Case Study

6.1 The Company and Its Supply Chain

In this article the intention is to shift the emphasis toward more practical aspects of the topic. Thus, it presents a project applied by a Greek Nireus S.A., which is now among the 10 largest fish farming companies in the world, towards improving total Logistics efficiency and sustainability [18].

Greece has a coastline of 15,021 km (covering more than 6000 islands and islets), and has a longstanding tradition and history in the fisheries and maritime sector. Despite its limited contribution (less than 3.1 %) to the gross domestic product (GDP), the Greek fisheries sector represents a primary sector of significant socio-economic importance, particularly in coastal, traditionally fisheries-dependent areas. In Greece, marine aquaculture is the largest aquaculture sector, in terms of both production volume and value. The number of aquaculture enterprises businesses totaled 1051 in 2012, while the fishery products processing sector were counting about 160 enterprises in 2007. These enterprises are located either in areas with traditional processing activities (northern Greece) or in big landing sites and consumer centers (Athens, Thessaloniki and Kavala).

With production facilities in Greece and Spain, the Nireus Group employs over 1200 people, to become one of the single largest companies in Greece. It exports more than 80 % of its fish to over 40 countries, mainly in Europe, but also in North America, Africa and Asia (www.nireus.com).

The production and the distribution networks are embodied in the Nireus vertical integrated value chain network (Fig. 2).

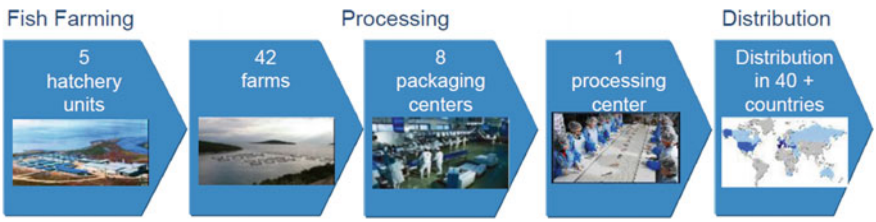
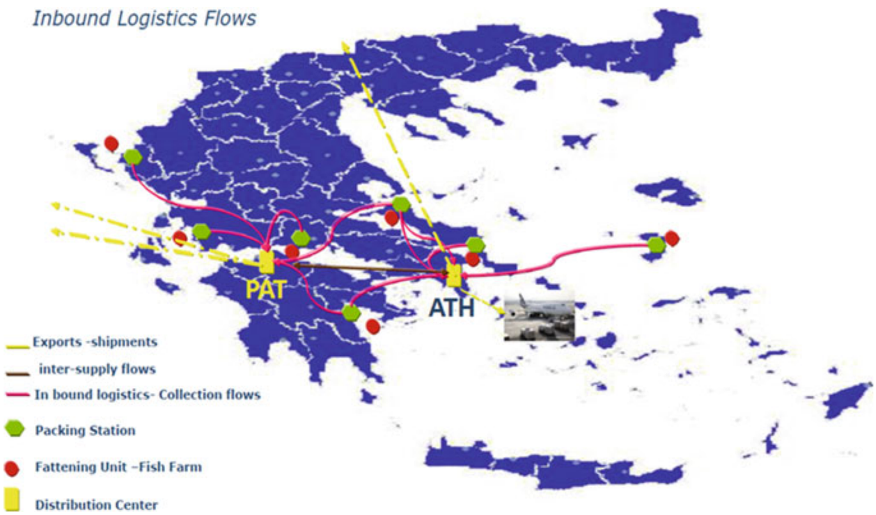


Fig. 2 Nireus vertical integrated value chain



Map. 1 Supply chain structure "as it was". *ATH* Athens, *PAT* Patra. *Source* Nireus Aquaculture S.A. [19]

The products are being harvested in the fattening units—fish farms. After the harvest the products are transported by boats in land bases and afterwards to packing stations. The farms and the packing stations are next by and places all over Greece (Map 1, [19]). The products are packaged and dispatched to the distribution centers.

6.2 *Supply Chain Restructuring*

The supply chain structure as it was is illustrated in map 1. More specifically, two distribution centers (DCs) in Athens and Patra, Greece, were supplied from the packing stations all over Greece (inbound Logistics). Then, from Patra DC they were transported by ship from Patras Port to Italy (Milan airport was used as a main cross point for exports all over Europe) and from Athens DC by plane to Eastern Europe and countries in other continents.

The analysis of the current situation, with the use of VSM tool, came out with the identification of non value adding and recommendations for redesigning the supply chain structure.

More specifically these were as follows and are illustrated in Map 2 [19]:

- Establishment of a new distribution center in Milan/Italy. Stopping all other co-operation with 3PLs firms in Italy. In the "old structure", there were three logistics providers per region (north, central, and East). The fulfillment of customers orders is taken place at Milan DC. In the new model, the order picking is done at night. The trucks arrive in Milan DC at midnight-a day after harvesting from Greece and the picking process is completed few hours after.
- Harvesting and packing volume of west part of Greece is directly forwarded to Milan DC through Igoumenitsa Port at the same day. Inbound flows from West Part of Greece to Patras DC or Athens DC have minimized.
- Use of Igoumenitsa Port facilities instead of Patras Port (Map 2, "IG", north west Greece).
- Most of the harvesting volume of Evia island Farms (two fish farms in central eastern Greece) is directly dispatched to Greek market retail chains and fish markets. 14 h after harvesting, the products are delivered to the customers warehouse even in the farthest point of Greece.

Comparing the total logistics time between the new supply chain structure with the previous one, a reduction of more 50 % has been achieved, contributing to total

Map. 2 Re-designed supply chain structure. *ATH* Athens, *PAT* Patra, *IG* Igoumenitsa. Source: Nireus Aquaculture S.A. [19]

product life cycle reduction of 25 %. This has led to significant cost reduction to both inbound Logistics (by 17.4 %) and domestic distribution per country (average cost was reduced by 26.5 % due to economies of scale in Italy).

Moreover, the company developed and implemented a new Logistics Software System which controls the packing stations warehouses in Greece at real time and on-line. The system is part of the Trace-ability system and gives the ability to the final customer to trace the product which bought from "Eggs to Selling Point". More specifically, a label/tag is placed on its gill and on the tag a QR code is placed, customized per country particularities as language, religion, habits and customs. Scanning the tag, it is ease to have information regarding the preserve of the fish/fishes, cooking instructions and recipes, freshness of the product/trace and truck of its history about Nireus company.

7 Discussion and Conclusions

The growth of the fish industry is earmarked by combined effects of changing structure, in increasing worldwide aquaculture volume along with declining wild fisheries, increasing world population and changes in consumer preferences. The topics that are of top interest in the aquaculture sector are associated with the future of the sector, since the global fish stock is in crisis.

In the very short term, the sustainability of fish products depends on two major elements [9]: a significant decrease in the pressure on stocks, and the actual implementation of traceability of fish from the point of catch to the shelves.

The former can be achieved through reduced fish consumption worldwide, which is not likely to happen, or through aquaculture, provided it becomes sustainable, i.e. it does not depend on wild catch for feed or regeneration and does not threaten ecosystems and respects equitable social conditions.

Fishery products differ from other products in view of that they are time sensitive: time is a critical factor in both production and distribution process, affecting the quality of the product, since freshness is of top concern in the consumers' purchasing criteria list, as shown in Fig. 1. Besides, according to UNEP [9], although the length of the supply chain can vary depending on the product and country of origin and final destination, in any case the shorter the physical and time distance from primary producer to consumer, the more transparent the supply chain. Of course, smoking, pickling, salting or canning can extend the fish supply chain even when the destination of the product is local.

Eliminating time "wastes" in the supply chain leads to significant cost and environmental benefits. Non value-adding activities and potential operational improvements can be identified using assessment/evaluation methods and tools, like LCA and lean techniques. Thus, this paper turns the attention to more practical aspects of sustainable aquaculture, and more specifically in the re-engineering of the supply chain towards increasing efficiency in terms of time and transparency. The success of a project experiment applied by one of the most important European companies in the aquaculture industry, relies on shortening the life cycle of fish, reducing the time gap between production and delivery to the customers. ‘Time-waste’ issues are identified throughout the supply chain, by applying value stream mapping methodology.

A key condition for a sustainable supply chain is that information related to sustainability issues (socio-economic and environmental) can reach those involved in a useable fashion. As probably the only mechanism allowing the transfer of information from one element of the supply chain to the other in a systematic way, traceability is a crucial and fundamental condition for sustainable supply chains, especially under changing and volatile conditions, asking also for resilience [20]—although traceability in itself is not sustainability.

Above all, the successful meeting of the historical sustainability challenge based on sufficient understanding of the critical factors that impact the aquaculture supply chain. The cooperation with supply chain managers and academics that are increasingly aware of such challenges, so that it is believed that the conclusions and recommendations drawn in this study will reveal the direction for further research towards integration of aquaculture development with the sustainability imperatives.

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Part VII
Invited Session 3: Eco-design Through Systematic Innovation

QFD for a SME Network of the Wood Sector to Improve Competitiveness and Sustainability

Gilda Massa and Nicola Gessa

Abstract The QFD methodology, in spite of being quite old, it is not widespread and tested in the Italian ecosystem, in particular in SME networks. In this paper we report our experience in the application of the QFD to a SME network in the wood sector, with the aim to improve the competitiveness and innovation capacity, and prefiguring a new way to collaborate in business relationships, finally increasing sustainably through a short supply chain; through the experience we highlight the QFD potentialities, as tested by the SME network in the definition and development of the first PEFC certificated musical instrument.

Keywords QFD · SME networks · Supply chain coordination · Wood sector

1 Introduction

The competitiveness of the Small and Medium Enterprises (SMEs) is fundamental for the development of the Italian and European economy, and nowadays for all of these enterprises the competitiveness strongly depends on the innovation capacity, the development of new products and services, the improvement of the overall quality. This perspective for the SMEs must be supported by new tools. The new technologies and the developments in the ICT field surely represent a big opportunity: new software and new communication means, Internet, mobile devices etc. are for sure some of the major weapons for a global, more interrelated, economy, but together with them a very relevant role is played by new business, organizational and operational models that could drive the enterprises towards a new way to collaborate and to approach the market.

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More specifically, for SMEs the right way to deal with the future challenges of the global competition is to face them with a wider and different vision of the dynamics that regulate their mutual relationships: the small enterprises should no longer perceive themselves as isolated and closed entities that fight with the neighbors to survive, like princes in medieval fortresses, but they should consider themselves as part of a more and more sustainable productive system in which collaboration and comparison could be very useful tools to be more effective in the market. Moreover, it is fundamental for the enterprises to improve their adaptability to the customer requirements, and to become more dynamic, able to rapidly follow the market changes.

In this context we present an experience of use and application of the Quality Function Deployment methodology (QFD) in a SME network of the wood sector. This methodology represents a powerful tool for the improvement of the product design phase; we adopted QFD in a SME network in order to build a stronger awareness, among the different actors of the supply chain, of the role of each of them on quality aspects in the whole production process. But this is just the first step, since the final aim for a SME network is to become more cohesive and competitive. Our effort aims also to highlight the role and the contribution that QFD can play for Eco-Design, as a tool for high-quality sustainable production in a SMEs context.

In this paper first of all we briefly summarize in Sect. 2 some aspects about the QFD methodology. In Sect. 3 we present the context of our work, and the main motivations and drivers for our use case. In Sects. 4 and 5 we describe more in details the approach adopted for the application of the methodology in our SME network, the tool we developed on this purpose and the main results directly arising from the experience. In Sect. 6 we show how this methodology has led us to the definition of a strategic plan that, exploiting the evidences arisen in the previous steps, can drive the network to a new configuration and a new way to collaborate in order to gain efficiency, product quality and customer satisfaction. Finally, in Sect. 7 we summarize our work and we report some conclusions and ideas for the future development of the activities related with the QFD application.

2 The QFD Methodology: Scope, Limits and Applications

Quality Function Deployment (QFD) is a methodology born in the context of the big Japanese industry and then developed in Europe and America in the 90s, as a tool and technical support for product quality design; Quality Function Deployment is closely tied to Concurrent Engineering and Lean Production, two methods that can reinforce “quality and innovation”. QFD is “a system for translating customer requirements into appropriate company requirements at every stage, from research through production design and development, to manufacture, distribution, installations and marketing, sales and services” [1].

QFD is a tool that can guide the design of a product to match the real needs of the users; in this sense it represents a clear and powerful way for setting structured and targeted projects, and its commitment normally precedes the development, industrialization and production of new products and services [2]. The complex relationships between customer requirements and technical attributes, and the correlation between different technical attributes can be illustrated in a typical "House of Quality" (HoQ) matrix. The HoQ serves to link the Voice of Customer (VoC) to engineering metrics (EM).

The QFD methodology has been used in many different scenarios [3] and recently is widely used in the context of environmental sustainability in: shipping context [4], remanufacturing (as the ultimate form of recycling) [5], logistic services [6], service quality in vegetarian food industry [7]. These are different applications with a common proceeding schema: firstly taking the voice of the costumer, often using interviews, questionnaires, market research (in order to define "What's" customers' need), then defining the product technical characteristics ("How's" it produced). The focus is to the company, generally a large company.

Although QFD can support the enterprises and the industry with relevant outcomes and contributions [8] the literature shows a limited adoption of it within the SMEs, especially in comparison with other "soft process technologies", depending also on the enterprise dimension and characteristics [9, 10]. This limit is due to the nature of SMEs and to the reduced involvement that most of them have in the design and development of a specific supply chain product. Many SMEs limit the vision of their own activities and their role to a simple customer-supplier relationship, without any awareness of the final product that is realized: the final market is often perceived far away.

3 The Need for Innovation in SME Networks of the Wood Sector

Europe's 23 million SMEs represent 98 % of business, provide 67 % of the work and create 85 % of all new jobs [11], so it's clear that SMEs hold the key for the economic growth. SMEs are often players involved in the value chain of a product without a clear awareness of their role and importance in the supply chain strategy, and sometime of what it means to be part of a network.

One of the factors that strongly marks, or perhaps we should say that has marked, the approach of a SME in a network, in particular in the Italian context, is the "individualism". But the individualism is leading, especially in this moment of history, to the death of many SMEs. The growth in size of the enterprises and the "aggregation" of the small ones are perceived by the entrepreneurs as essential elements to survive, even and more in an internationalization perspective.

In this context, the Italian government has deliberated with the establishment of the so called 'Network Contract' ("Contratto di Rete") in Law 33 of April 2009.

The law says that, with the Network Contract, two or more firms undertake in common one or more economic activities, sharing objective and mission, in order to increase mutual capacity in innovation and competitiveness on the market [12]. The Network Contract is thus a tool to regulate and stimulate the collaboration and the "aggregation" between the SMEs, however maintaining distinct enterprise identities.

There are many business sectors that need to converge towards this new collaborative approach between SMEs: in particular in the wood sector (that is our focus) strengthening competitiveness is one of the priorities, as in the EU Forest Action Plan [13, 14].

The aim is to achieve a better management of the forests of the Community, while maintaining and strengthening the multifunctional role of the forests through a new consciousness of the value of the wood: to provide renewable raw materials, to define sustainable production processes, to support, especially in rural areas, territorial economic development and employment and to preserve environmental resources are the main key points of this initiative. The Plan has four goals, divided into 18 key actions and 53 activities. It recognizes the need for specific approaches and actions, emphasizing the important role of the owners in the sustainable management of the forests; it encourages innovation and research activities, specific training for forest owners and workers, it proposes measures aimed at optimizing the use of forest resources for energy production, also including specific elements that contribute to the achievement of environmental objectives related to the issues of the climate change and the biodiversity.

This vision is followed by the Italian framework program for the forestry sector (PQSF) [15], which has the overall objective of encouraging sustainable forest management in order to protect the territory, mitigating climate change, activating and strengthening the forest industry and ensuring long-term the multi-functionality of the forest resources [16].

Our use case of the QFD application is strongly related with the implementation of the priorities of the European Plan and the Italian framework program for forest management through the Network Contract.

4 QFD for SME Networks

ENEA, the Italian National Agency for New Technologies, Energy and Sustainable Economic Development, comprises many different laboratories that conduct research and innovation activities concerning energy efficiency, renewable energy sources, nuclear energy, environment, sustainability of productive systems. Within the agency, our laboratory, the ENEA DTE-SEN-CROSS lab, provides some support services for SMEs, networked enterprises and productive districts. Among these services we propose the QFD methodology application, with a new perspective: QFD for SME networks; the idea is to view a supply chain, or a SME network as a Virtual-Enterprise, where each actor represents a fundamental member for the realization of the final product, like different departments in a complex industry. In this perspective efficiency and competitiveness are achievable only if the different actors, always maintaining different identities but with the same dignity, collaborate not in a competitive but in a collaborative way.

ENEA QFD approach is applied to overcome individualism and to introduce more strongly the customer point-of-view in the supply chain production processes. Analyzing a product according to the customer-firm vision is fundamental to innovate and to compete. But this is not enough: in the context explained in Sect. 3, QFD can be viewed as a way to promote and enforce territorial districts, local networks and the sustainability of the productions.

To this aim the three basic points that drive our activities about the QFD methodology are:

- To constantly improve the collaboration and the information exchange between the partners, in order to define and share business strategies among the whole production chain. Partners that are not involved in the management and design of the network strategies cannot understand the needs and the requirements coming from the market and then are less disposed to react and to modify their processes to face supply chain issues.
- To highlight the economic advantages, for all the partners, that overcome the difficulties and the issues coming from this new approach in relationship management, thus ensuring more fruitful and active involvement of each partner (also the smallest ones) in the supply chain activities and production.
- To align the interests of a network or productive system with the interests of each partner, providing a shared vision of the market. In a SME network in fact enterprises (nodes) that are far from the final market have no awareness about its requirements. This negatively affects the product quality and the responsiveness of the network to market change.

Other results that directly come from the previous main points, and that can be the final objectives of such activity, are also: supply chain integration, definition of a new network brand, brand localization, internationalization, product innovation, new commercial channels.

5 Applying the QFD Methodology on the Wood Sector

The application of the methodology has followed several steps. In this section we summarize its application in the wood sector.

Although the QFD methodology is based on a clear set of principles and concepts, and in the main lines it is well identified, the specification of the details and the formalization of the procedures and the steps can vary depending on the needs of the analysis and the context. Then, our first phase concerned the customization of the general approaches found in literature to formalize the specific formulas to use to perform the study. Obviously the core of the QFD remains the adoption of the requirements/technical-characteristic matrix and the House of Quality. On the other hand, we skipped some aspects of the methodology also in order to make it more simple to use during the work and the discussion with the SMEs. The fundamental point remained to reach a clear identification of the "conventional value" for the products to analyze.

After the definition of our custom version of the QFD methodology, we needed a software that would help us calculate the formulas. Although many implementations are available online (see for example [17–19]), and some of them are free, in the second phase we decided to proceed for a custom implementation that could be tailored for our purposes; the implementation was not complex, difficult or time waste: as many available solutions, we opted for an Excel-based implementation. Excel in fact provides a simple and natural way to develop a software for QFD calculation.

The third phase has regarded the network and node analysis. The starting point for a fruitful QFD application is a complete vision of the network and of the enterprises, in order to have a comprehensive knowledge of the role of each partner, their competencies, their process and organizational structures, their relationships, their weakness and strength points, the target market, also to facilitate their involvement in the network activities. In this phase the role of the Network Manager is essential, since it acts as a glue to connect and mainly involve the partners.

Our use case regarded 9 enterprises, distributed throughout the wood supply chain, with different roles: from the woodman that procures the raw material in the forest, to the sawmill, the consulting company for forest management, and the enterprises that provide the final products to market; in particular we analyzed several final nodes of the chain and we considered some different products of the supply chain, in order to identify those on which to apply the QFD. Among the available alternatives we finally focused the QFD on a wood-based musical instruments: the harpsichord.

Once we got in contact with the enterprises, in the fourth phase we organized a 2 days' face-to-face workshop in order to join the different perspectives and competencies in the elaboration of the QFD analysis. Again, involve each partner is fundamental, but even more it is very important both to convince the participants of the opportunities provided by the QFD and that the analysis have to be as much as possible objective and honest, in order to discover the criticalities of the supply chain, instead of to underline the strong points. The analysis allowed us to highlight all the components, coming from all the supply chain, that determine the quality and the specificity of the harpsichord, with the evaluation of the crucial points to develop and the strength to enhance.

The results of the analysis showed the key role of the raw materials and so we decided to do another QFD analysis focused on the trunk. This specific decision has been taken and implemented due to the attendance of the first nodes of the supply chain, the woodcutters, that have the specific know-how and competence on the trunk. This second-level analysis is possible only in our approach in which we created an aware collaborative working group and we involved all the nodes of the

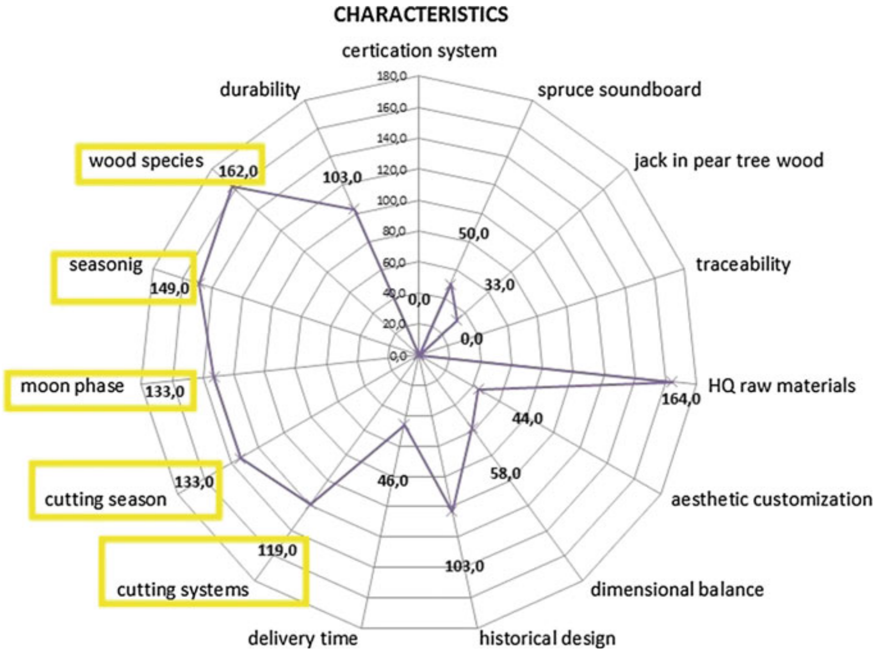

Fig. 1 QFD analysis for the product "Harpsichord"

SME network, in particular all the first elements of the value chain, that depends on woodcutter role end experience.

Wood species, moon phase in cutting, seasoning, cutting season and cutting systems are all characteristics (highlighted in Fig. 1) directly connected with high quality raw materials that, coming from the network nodes, disappear in QFD done within a big organization. The figure shows the intermediate results, with the evidence of the role of the raw materials in the harpsichord.

We also performed a first comparison with the products of the competitors. The workshop ended with a complete QFD analysis of the 2 selected products (the trunk and the harpsichord).

After the end of the workshop, the following phases regarded the analysis of the evidences arisen from the QFD application, in order to elaborate a strategic plan.

The application of the methodology highlighted two critical issues during the workshop, the first being the presentation of the house of quality that seem to be, in the first step, complex for small business owners; the second one is the definition of the values of the characteristics since, if the characteristics are qualitative, sometimes they could be overestimated for their own product.

Regarding the implementation phase, the main difficulty was instead the definition of product requirements because the involved SME, and SMEs in general, don't have a specific commercial unit, market analysis, questionnaires and tools to collect and evaluate in a structured model the voice of the costumer.

6 From the QFD Analysis to the Strategic Plan

A company business strategy can be defined as the way to draw future scenarios, to face the competitive environment and to exploit the resources and opportunities.

In general, talking about strategic plans and objectives for business networks and SMEs is difficult: often the decisions are imposed by the entrepreneur and often few persons take the control of the whole company; a more structured approach to strategy definition is not applied and the company activity is driven mainly by fiscal and financial considerations: the object often is to survive rather than to gain a strategic position in the market.

We start from the results of QFD to define a business strategy for market positioning and promotional policies for a SME network.

From the matrix of relationships (in the HoQ) we determine the "conventional value of the product" [20], that is a no dimensional indicator that summarizes the technical quality of the analyzed product and allows to understand how much a product is able to match with the customer quality requirements.

Once we get the conventional value of the product of the SME network and of the competing products we make a further comparison taking into account the cost and/or the price for the consumer, considering the two "values per unit price", calculated with the following formulas:

$$\frac{Conventional\,Value_{Our\,Product}}{Price_{Our\,Product}} = \frac{Conventional\,Value_{Competitive\,Product}}{Price_{Competitive\,Product}} \tag{1}$$

This comparison is quite complete (it takes into account all the information entered into the relationship matrix), and above all it is very easy to do and very straightforward to interpret; this last feature is very valuable in a decision process which involves many partners, as in a SME network.

The market repositioning of the SME network may be done modifying the market price (the denominator of the value), or changing the "value" of the product characteristics (the conventional value in the numerator).

If the strategic decision of the network is to modify the product, the next step is to decide which characteristics have to be changed and to what extent. It is clear that, in principle, those characteristics which have a bigger relevance (or weight) should be considered first, to have more substantial improvements in the product value. But it is also clear that also the evaluation of the cost variations, and therefore of the price, should be considered to make the comparison more convenient in terms of value per unit price.

The most interesting case regarded the application of QFD methodology to the design of the harpsichord. The musical instrument resumes the design of the original model "Giusti 1681" and the QFD analysis allowed us to highlight the quality parameters of the instrument and to correctly evaluate with the SME network (named 12/IT-01-01 network [21]) the market price and the market penetration strategy, taking into account the value for unit price paid.

Specifically, having a "conventional value" of 5194 and compared with 4839 of the concurrent product, the harpsichord Leita Brothers has shown to be in general 7 % more responsive to customer requirements respect with that of the competition.

From QFD analysis, the raw material characteristics emerged as a relevant factor, that led the network to another fundamental strategic choice: to improve the product quality perceived by the customer.

To this aim the network decided to preserve the Chain of Custody throughout the whole production process, leading to the creation of the first musical instrument certified PEFC (Programme for the Endorsement of Forest Certification) [22–24]. The strategic choice is based on another fundamental pillar, the short supply chain (that contains within a few kilometers the entire production process) and the traceability of the whole production (conforming to the "12-to-Many" © network model) [21] for the creation of a sustainable and high quality product. The network 12/IT-01-01 responds to the harpsichord master desires with a harpsichord conforming to the technical and mechanical characteristics of the original "Giusti 1681", giving particular relevance to the solid wood in a short supply chain that allows both to improve the intrinsic product quality and to emphasize sustainability aspects. In this sense QFD could represent a powerful tool for Eco-design, as it naturally supports collaborative design among the partners in localized SME network, exploiting local competencies and promoting short supply chain. In the outlined use-case, QFD allowed also the optimization of raw material usage and, thanks to the application within a network of strongly related partners, the waste materials could be exchanged and reused in different ways from the enterprises. In the case of harpsichord, all the raw materials came from the local area, and this led to the production of a high quality, eco-friendly, market competitive product of sophisticated design. All these characteristics are not exclusive, but with the right approach can be implemented in a single product.

7 Conclusions

Supporting SME networks to face the global competition is fundamental for both the European and Italian economy. To this aim ENEA DTE-SEN-CROSS laboratory has developed and provides a set of different services for the SMEs. One of the services that we have refined and we are now testing in practical case is the assistance in application of the QFD methodology. This methodology is well-known and quite consolidated from the past in single industry, but our effort is devoted to its application in the context of the SME networks, in which the experiences in Italy are lacking. In this paper we present our approach and use-case in the wood sector. In this experience we improved the network partner collaboration and we supported SMEs to facilitate the product innovation in the supply chain, to improve the product quality, the competitiveness in the market and the responsiveness to final user requirements, to highlight the criticalities in the production process along the whole supply chain. In our experience we have experimented a new awareness and interest of all the partners towards the issues related with the whole supply chain, and the QFD application has proven useful for the analysis of the product value and to identify possible interventions on the product characteristics. Each partners has deeply understood the role and the high strategic value of the trunk to reach, for the harpsichord production, the goal of a high sustainable product made from certificated Italian wood and with a short value chain.

This analysis has led us to the definition of a strategic plan, which finally represents the intervention mechanisms for supply chain innovation, that it has been well-accepted and translated in the first PEFC certificated musical instrument. On this activity, we will keep on testing the QFD on other SME networks to evaluate different approaches in presenting the methodologies and we are now considering to integrate the QFD in the development of a decision support system.

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Using TRIZ to Combine Advantages of Different Concepts in an Eco-Design Process

Pierre-Emmanuel Fayemi, Claire Vitoux, Malte Schöfer and Giacomo Bersano

Abstract The intended goal of the publication is to evaluate the relevancy of tools originating from TRIZ to integrate transitional representations in an eco-design process. It is expected that TRIZ tools could allow the project team to take into account all the identified constraints regardless of the discipline they are coming from. The methodology aims at providing solutions which fulfill the different perspectives (engineering and industrial design) without trade-offs. To do so, transitional representation during early design phases must enable the integration of multiple idealities in the context of multidisciplinary product design process.

Keywords TRIZ · Eco-design · Multidisciplinary · Transitional representation · Industrial design

1 Introduction

The design of new and complex products needs the cooperation of different and distant fields of expertise. In this context, it is necessary to take into account this multidisciplinary factor since the earliest stages of the project [1]. The involvement of multiple expertise allows to identify the goals and constraints that have to be

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taken into account in the final product design. Even if some studies are already addressing the issue of cooperation between distant fields of competencies [2], this project-related aspects are still a problem for design teams.

The need for different capabilities and the wide diversity of stakeholders in a project is even more critical in the context of an eco-design process that aims at creating a sustainable and eco-friendly product.

The present work aims at enhancing the integration of constraints from different fields of expertise in the context of an eco-design process. The paper will describe the method and its application to an industrial design project of a floating solar panel system.

2 State of the Art

Today's R&D activities are characterized by a diminution of boundaries between industrial design and engineering. One approach used in this context is Kansei engineering, the assertion of users' feeling in tangible properties [3]. In this context of merging disciplines, problem solving is related to the use of expertise originating from distant domains and could benefit from the theory of inventive problem solving (TRIZ) [4, 5]. We could find no literature or previous research on the use of TRIZ to allow the integration of design parameters, originating from industrial design, during early phases of multidisciplinary projects.

2.1 Basic Concepts of TRIZ

System development, and the use of available means to perform required functions are some of the key concepts of TRIZ [6]. This paper will focus on three specific concepts, the first two being ideality and contradictions. These two concepts allow designers to outline the quality of an idea in an innovative multidisciplinary design framework. The third is "hybridization", which allows merging two alternative concepts into a single relevant one.

2.1.1 Ideality Through the TRIZ Perspective

The concept of ideality is presented in TRIZ as:

- the ideal machine which has no mass or volume but accomplishes the required work
- the ideal method which expends no energy or time but obtains the necessary effect in a self-regulating manner
- the ideal process which actually is only the result of the process without the process itself.

Based on these points, the Ideal Final Result (IFR) represents the absolute best solution for a problem under the given conditions [5].

The IFR is a fundamental notion for the implementation of problem solving tools. According to Newell and Simon [7] the advantage of working backwards in such problems is that there is no ambiguity as to what statement to start with. The more a designer is able to define precisely the ideality the easier will be the search for ideas.

2.1.2 Contradictions

As a basic concept for effective problem solving, TRIZ has developed some mechanisms for directing the solver to most appropriate and strong solutions; contradictions are one of these key concepts. The problem analysis emphasizes the contradictions to solve, in order to make the system evolve through the IFR. Three types of contradictions exist [5]: administrative contradictions, technical contradictions and physical contradictions. Administrative contradictions consist of problems as formulated to the designers; they are usually poorly stated and do not point in any direction. The technical contradictions oppose two correlated evaluation parameters (EP) of a given system: every solution that improves one EP worsens the other EP. Physical contradictions involve an internal design parameter (DP) to solve the problem which is expected to accept two opposite states (or values) (e.g., a ladder must be tall to reach a sufficient height, yet small to be stored in limited space). Once contradictions to solve are clearly stated, designers, by following the TRIZ approach, have access to multiple tools to find principles of solution. The table of technical contradictions (or matrix) offers 40 inventive principles [5] to solve such contradictions. To overcome physical contradictions, TRIZ also offers to designers 11 separation principles [5].

2.1.3 Hybridization

The concept of Hybridization is a means to make technical systems evolve. In order to find an inventive solution, a designer must identify the resources necessary to provide the missing function. The search of resources from alternative systems is the essence of this approach; once an alternative system is identified, the resources it uses are transferred into the initial system, solving the contradictions that would eventually appear [8].

2.2 Transitional Representations in Design

In design, graphical representations are, like analytical documents or semantics, transitional design objects. Transitional representations are commonly used in the design field as well as in engineering, even though the translated information differs significantly. Engineers make use of schemes and standardized representations, as a tool to define the product and to communicate with other stakeholders. Industrial designers tend to use less standardized representation, such as sketching, in order to capture, synthesize or communicate ideas. Even though transitional representation properties differ, the transitional objects fulfill three roles: translation (diffused in the two other roles), action statement (synthesis) and mediation [9].

2.2.1 Transitional Representations as Synthesis Tools

Sketching is usually considered as a central step in the design process. For simple elements, sketching has little to no positive impact on a designer's creativity or on concept quality [10]. Kokotovich and Purcell however underline the importance of sketching for complex design tasks where multiple parameters need to be successfully matched.

Sketching is then considered as an analytical task [11] by illustrating the component of a system to be designed, leading to the identification of the remaining significant loopholes of the project.

2.2.2 Transitional Representations as a Mediation Tool

Transitional representations allow stakeholders to interact with each other [11]. By using transitional representations, actors from a variety of backgrounds can react and exchange using a common language. Transitional representations are becoming the principal means of negotiation among designers [12], used as a tool to generate consensus.

3 Case Study

The project FLOTA (Floating Offshore Photovoltaic systems) addresses the industrial problem of the autonomous supply of sustainable energy for the quickly increasing sector of fish farms. The market of fish farms or aquacultures bears enormous potential. It is expected that nearly two thirds of the global supply of food fish will be provided by fish farms [13]. This growth will induce the need for decentralized generation of energy, which the innovation project is able to provide, see Fig. 1.

In this context, it is essential for the product to be eco-designed. In order to reach the minimal environmental impact, the French Standard NF E 01-005 [14]—Eco conception for mechanical parts, has been implemented. The use of the standard has led to several modifications such as the choice of recycled polyethylene.

Fig. 1 FLOTA concept in fish farming application

The initial version of the floating solar panels presents many advantages. The developed design allows the system to be flexible: the modules can be replaced independently, and the "electrical farm" can be easily adapted to the energy requirements. The structure in itself has a very low impact on its environment: the floating photovoltaic panels are directly moored on the fish farm. They can also be used outside a fish farm context and can be attached on moored buoys.

The system could be more generally applied to every sea activity requiring electricity. Another potential application is the reduction of fresh water evaporation. Fresh water evaporation is a critical problem for countries situated at lower latitudes. According to various models, the principal causes of evaporation on a dam are solar energy and wind. Consequently systems capable of shielding the sun and the wind can reduce water evaporation significantly. Various systems are under development [15] in this context, the FLOTA system can also realize this function.

The European Commission has supported the project through the H2020: blue growth initiative. The publication details the finalization of specific design activities that has been carried out to allow the creation of a small scale demonstrator.

4 Application and Results

4.1 Method

The method focuses on using TRIZ to combine different idealities coming from different fields of expertise, here engineering and industrial design (Fig. 2).

During the first phase, each expert identifies problems to address and the main constraints (from his point of view) to integrate to the final concept. Constraints lead to the definition of idealities. This preliminary work is carried out independently by the different experts.

The second phase consists of conveying the identified idealities (and descriptive parameters) to transitional representations (drawings). This phase aims at comparing the different idealities to identify the contradictions to solve.

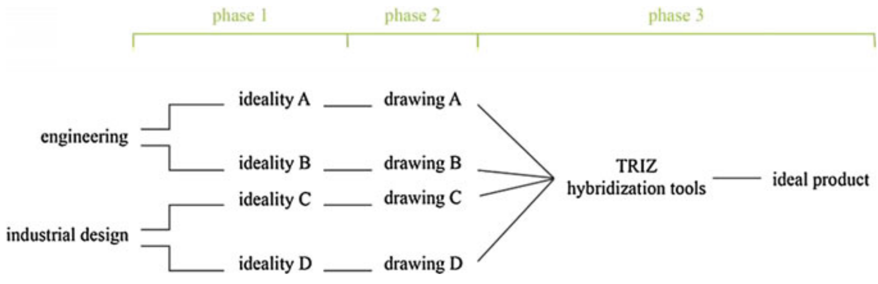

Fig. 2 Overview of the proposed method

On the third phase, experts, regardless of their expertise, cooperate in order to combine the advantages of each ideality to design the final concept thanks to the concept of hybridization.

4.2 *Protocol*

The method is applied to the eco-design process of a floating solar panel system. The project involves two main fields of competencies: engineering (optimization of a device's functions) and industrial design (ergonomics and aesthetics aspects). Expertise in engineering is brought by a junior engineer specialized in energy systems, industrial design capabilities are brought by an industrial designer specialized in product design.

The engineer and the industrial designer did not have eco-design expertise prior to the case study. The FLOTA project and its fish farm and dam applications are thus sufficiently described to identify objectives to fulfill as well as related constraints.

4.3 *Results*

4.3.1 Phase 1: Ideality Definition

The engineering analysis has led to the identification of two main constraints to take into account to design the final concept: the product has to produce the maximum of energy, and must reduce water evaporation (due to the specific application for the saving of drinking water). This ideal system already shows some contradictory design objectives: in order to produce as much energy as possible, the solar panel requires cooling and the module has to use heat transfer between the panel and the water, while for reducing water evaporation, the module must avoid the heat transfer from the panel to the water. From an eco-design point of view, both constraints have to be considered as they both have an impact on sustainability. On one hand, cooling the system by encouraging heat transfers from the panel to the water should prevent the panels from overheating and therefore degradation of efficiency. This leads to an increased product life expectancy. On the other hand, preventing heat transfer from the panel to the water reduces the impact of the system on its environment during its operational phase.

4.3.2 Phase 2: From Idealities to Transitional Representations

Schematic representations has been drawn, see Fig. 3, to formalized both engineers and designers ideality. These transitional representation will then guide the final design of the product.

The constraints from the engineering field are expressed into ready to be drawn physical characteristics. The four downgraded idealities are thus represented by four individual drawings or set of drawings which summarizes all the constraints to be integrated to the final product.

Concept A allows the system to reduce the heat transfer from the solar panel to its surrounding water. This inhibit the water in contact with the product to be warmed up. Concept B maximizes the heat transfer between the solar panel and the water by maximizing the exchange surface. In this way solar panels increase their energy production by decreasing the temperature of their solar cells. Concept C tends to reduce the visual impact of the system in the landscape by having organic shapes. Concept D underlines the function (energy production) of the product with very technical aesthetics.

The transitional representations allow anyone working on the project (either engineers or designers) to identify the physical and technical contradictions that appear when the different idealities are compared.

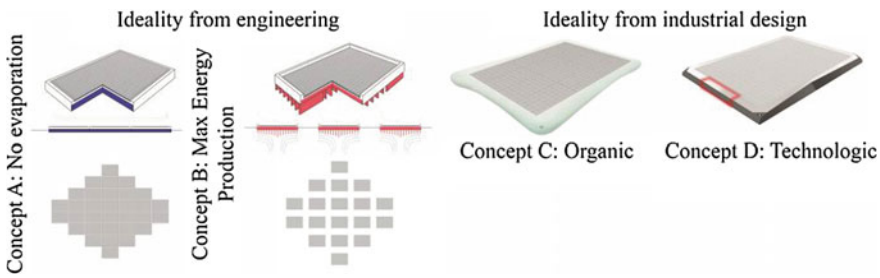

Fig. 3 Drawings of the downgraded idealities

4.3.3 Phase 3: Hybridization of Partial Idealities

Some of the listed partial idealities appear to be compatible. Ideality A shares common advantages and drawbacks with ideality C and the same holds true for ideality B with ideality D. No other compatibilities could be established among these partial idealities. Considered as clusters A/C and B/D remains relevant with their respective ideality.

The first cluster aims at reducing the impact of the system on its environment during its using phase. The second cluster aims at maximizing the energy production during the product's use phase.

As the idealities and concepts can be combined by pairs, it is possible to define one global concept per cluster, which holds the properties of the 2 idealities. As a result, it is possible to make an intermediary representation of these two concepts that synthesize the 4 idealities defined, as shown in Fig. 4.

Concept 1 is a module presenting organic shapes (inspired by fish scales) which reduces the space between two modules. Each "scale" overlaps the next one to avoid the water evaporation and to maximize the isolation between the solar panels and the water. It is built with insulating materials to make sure no heat transfer from the panels to the water occurs. When the modules are in their operating condition, they appear similar to fish skin. Concept 2 is a module presenting technical aesthetics. The panel is very efficient at producing energy thanks to the fins that conduct the heat from the panel to the water. Both aesthetics and technical design are made to optimize the production of energy. As the production is maximized for one panel, the environmental print of the energy produced is reduced. First, the module produces more energy during its using phase. Second, by evacuating the heat from the panel, the risk of the whole system to overheat and therefore panel maintenance is reduced.

Merging compatible idealities can be easily made, yet, in our design case, it only provides two different concepts with divergent advantages and antagonistic characteristics, as shown in Table 1.

This makes it difficult to agree on a single final design, without considering trade-offs. Considering that both concepts carry out the same primary function, converting solar energy into electric current, while possessing different deficiencies, it is possible to hybridize concept 1 and concept 2 into a final concept which is as close as possible to an overall ideality.

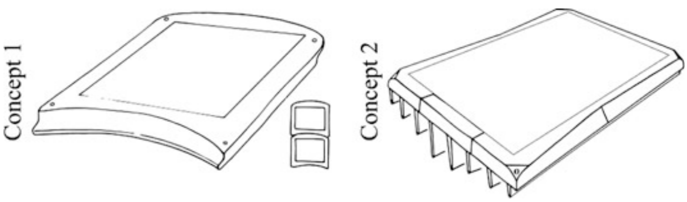

Fig. 4 Drawings of concept 1 and concept 2

Table 1 Advantages and drawbacks of concept 1 and concept 2

	Concept 1	Concept 2
Advantages	– Do not heat the water – Reduce air/water exchange surface	– Panels are cooled – Modules do not have mutual thermal impact
Drawbacks	– Panels are not cooled – Panels heat each other	– Panels heat water – High air/water exchange surface

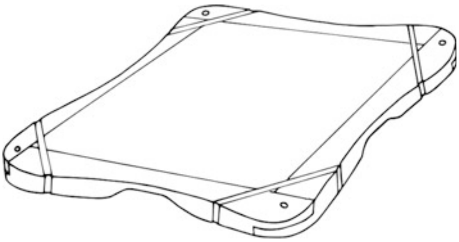

Fig. 5 Drawing of the final concept

To do so, the final concept should solve the following alternative contradictions:

- Limit the floater surface while avoiding modules to have a thermal impact on each other.
- The floater does not warm up the water while having its photovoltaic cells cooled.

The use of the Algorithm of Consecutive Combining [16], used in a creativity session has led to a final concept, see Fig. 5.

The final concept, is designed as 4 identical independent floaters with a solar panel on top. The general shape is based on organic inspiration while the supports integrate the technologically inspired properties, with connectors displaying proper connectivity indicators and night signals. The panel is fixed on the module by elastic bands on each corner. The floats are design to allow an air circulation between the panel and the water surface. The floating solar panel system can be transported as independent parts to be assembled on site. When the 4 modular supports are fixed together, they form the floating frame on top of which the solar panel is fixed thanks to elastic stripes (see Chap. 3). This configuration allows the air to move between the solar panel and the water.

The final concept combines advantages of concepts 1 and 2, as shown in Table 2.

The thermal impact that modules may have on each other could not be transposed to the final concept. The purpose of this advantage was to increase the life expectancy of the product. However, the new modularity induces a longer lifespan as parts of the system may be replaced in case of breakage. This wasn't a possibility with concept 2 and thus compensates the non-transposed advantage.

Table 2 Concept 1 and 2 hybridization results

	Targeted advantages	Provided advantages
Concept 1	No heating of water	Thin air layer between water and photovoltaic cells
	Reduced air/water exchange surfaces	Modules stackable with high density
Concept 2	Panels are cooled	Air-to-air heat exchanger
	No thermal impact of modules on each other	

Table 3 Pre and post redesign assessment with NF E 01-005

Criterion	Benefit(s)
Raw material	Good: the 4 modular supports require 20 % less material than the initial device (no support to glue the panels on is required)
Production	Good: smaller molds can be used
Use phase	Good: facilitated maintenance, any part of the system can be individually replaced
Substances	Good: the final concept does not require the use of glue
Packaging	None
Transportation	High: supports require less space and can be more easily stacked during transport
End-of-life	Very good: longer lifespan, any part of the system can be recycled individually

The final concept has been compared to the initial FLOTA concept. The assessment used French Standard NF E 01-005, from which has been developed the initial concept. Results of the eco-design improvement through the application of the method are shown in Table 3.

5 Conclusion

The eco-design approach, enriched with the use of ideality and hybridization as described by TRIZ, allowed to combine constraints from different fields of expertise considering the floating solar panel system. The constraints have been first identified by an engineer and an industrial designer, expressed as idealities, and then illustrated through transitional representations. These representations allowed to identify contradictions and then to address them by the concept of hybridization. At the end of the process, the floating solar panel system fulfills all the objectives and constraints, without any trade-off. From an eco-design point of view, the final concept presents the advantages of all the idealities defined on the first phase of the method.

The purpose of the described method is to combine constraints from different fields of expertise (engineering, ergonomics, aesthetic design, production, etc.), while preserving their respective advantages. If we consider the final results from the solar panel design case, they are globally satisfying. The process allowed the different fields of expertise to collaborate in order to design an eco-friendly product that provides all the eco-advantages of the different previously defined partial idealities. However, in our case, the fields of competencies were few, and close to each other. If the method seems to be conclusive in this particular case, it needs to be tested on a more complex project with the involvement of a wider range of distant expertise.

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Is TRIZ an Ecodesign Method?

D. Russo, M. Serafini and C. Rizzi

Abstract Several Ecodesign methods can be found in literature, though none has ever really established itself industrially. On the other hand there is a plethora of methods for problem solving which do not necessarily produce greener solutions. Among these, the most promising is the TRIZ methodology for inventive problem solving. TRIZ is not meant for Ecodesign, but recently more and more eco-applications can be found in the literature. This paper aims at providing a new interpretive key of the TRIZ methodology from an environmental point of view, to distinguish which tools and principles are readily applicable to Ecodesign from those that need to be customized. A detailed analysis of the best-known tools of the methodology applied to Ecodesign is presented, as well as how they have been integrated into a single operational tool called i-Tree.

Keywords TRIZ · Ecodesign · LCA · Environmental assessment · Environmental improvement

1 Introduction

Ecodesign represents a challenge that technicians are trying to face since the cost of products or processes has started to include the total environmental cost. Ecodesign is mainly a matter of resources (exploitation or saving) and emissions, and a design properly based on this concepts can lead to notable "green" results even without using any ad hoc "green" methodology.

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There are several reasons, not necessarily technical, why designers do not think green but design products or processes that generally make a bad use of resources. The most frequent reasons are:

- Starting requirements are overestimated, making the product works beyond the real needs (think of a vacuum cleaner that remains at full power even when it goes on clean surfaces or a car idling in front of a red traffic light). This is due to a lack of knowledge or excessive assurance or useless extra features.
- The evolution of a product does not take place in a linear way. Each subsystem is developed at different speeds. Design of sub-systems is done separately and, as a result, some resources will be inefficient or redundant, and sub-systems will scarcely interact until sufficiently mature.
- Traditional design is used to solve technical problems by adding additional devices, rather than rationalize the product eliminating the parts that produce undesirable effects. Because of this, unsolved problems bring over complication of product or process and imply poor cooperation of parts. It is quite common to see how the more mature a system is, the more elements are not contributing to the final function that the system has to perform, but they are instead dedicated exclusively to support the system in its accessorial functions.

These and other causes deeply affect sustainability of the product. Actual products waste a significant amount of material, energy and space that could be saved to decrease their impact on the environment. To date, the efforts of the community have produced two types of tools for Ecodesign: one focused on eco-assessment through statistical elaboration of material and energy data (e.g., Life Cycle Assessment, Life Cycle Design Strategy Wheel), the second, mainly experience driven, focused on innovating the system to achieve a better eco result (e.g., Ten Golden Rules, Companies Eco-Guidelines). What is missing is an integrated method answering both issues with a systematic, practical and efficient approach. Thus, an adequate methodology to address Ecodesign issues must be as strong in assessing as in providing new answers to push evolution in the right direction.

Rather than introducing another new approach for Ecodesign, the authors identified in the TRIZ theory a tested and versatile method for this purpose. TRIZ is a problem-solving, analysis and forecasting tool derived from the study of patterns of invention in the global patent literature [1–3]. Some recent attempts in the literature confirm this thesis; however, TRIZ application in Ecodesign has been shallow and very specific. The aim of this paper is to explain the real potential of this method and show a practical application of the new approach based entirely on TRIZ. First, the paper provides a critical analysis of the state of art related to TRIZ in Ecodesign. Then, we describe how some TRIZ tools that can be profitably used to design greener products.

2 State of the Art

The TRIZ methodology has been successfully applied to Ecodesign, primarily as an aid to Eco-improvement. One of the most common TRIZ tools is the 40 design principles, derived from a comprehensive analysis of patents. Strasser and Wimmer [4] worked on the combination of Ecodesign and inventive principles to develop environmentally conscious products.

The 40 inventive principles may be applied independently or together with the **contradiction matrix**. Chang and Chen [5] proposed an Eco-innovating method based on a design approach using TRIZ contradiction matrix. Kobayashi [6] applied contradiction matrix as an idea generation process at the product level for life cycle planning (LCP). At a higher level of detail and abstraction, **laws of evolution** have been applied to Ecodesign. Altshuller [2] studied the way technical systems have been developed and improved over time. From this, he discovered several trends (so called Laws of Technical Systems Evolution) that help engineers predict the most likely improvements that can be made to a given product. Russo et al. [7] described a way to use concepts and tools of TRIZ to assess, evaluate and innovate a technical system so that some practical activities to ensure sustainable results can be easily embodied into everyday design practice. The main novelty on the operative level consists of an original method based on a set of Guidelines derived from Laws of Technical System Evolution (LTSE), in order to assess the value of existing solutions, understand the most promising directions of improvement, and improve existing solutions according to environmental requirements. Chulvi and Vidal [8] compared the trends of evolution in TRIZ with ecodesign strategies, named LiDS Wheel (Life Cycle Design Strategies), to analyze the effects on environmental parameters. With regard to eco-innovation, Low et al. [9] utilized TRIZ evolution patterns to explain the relationship between service and product function. Chen [10] developed an eco-innovation method by incorporating ideality laws and green evolution rules to create products that are environmentally friendly. Justel et al. [11] utilized TRIZ evolution rules to reason the evolution of joint parameter for disassembly. Fresner et al. [12] used TRIZ Ideal Final Result (IFR) and the Laws of Evolution in cleaner production to minimize industrial waste and emissions by increasing the efficiency of the use of materials and energy. Yang and Chen [13] combine the innovative incremental design achieved with Case-based Reasoning (CBR) and TRIZ tools, with particular attention to the evolution trends.

Only few works try to devise a **comprehensive TRIZ based approach**; not founded on a single TRIZ tool, but revised from the ground up to take full advantage of the TRIZ methodology. The work of Yang and Cheng [13] described a new model to accelerate the preliminary design of the eco-innovative product by incorporating the benefits based upon case-based reasoning and the TRIZ method. Several examples of ecodesign are given to illustrate the capabilities of such a method already starting with the work of Chen and Liu [14]. Another attempt at a more integral TRIZ based approach was made by Chou [15]. Chou uses the ARIZ algorithm to restructure a set of new product models through modular analysis of alternative attributes, including a dedicated assessment method that integrates the three dimensions (technical, economical, and environmental) of LCE (Life Cycle Engineering) analysis into a single decision support tool. Finally, Mann and Jones [16] presented a case study that enhanced product service and use service in an energy system. They state that "The evolution of sustainable service systems demands an increasingly holistic approach to the design process, that requires the original definition of 'the system' to be extended to include a super-system".

To date, TRIZ cannot be called a methodology for sustainable design, because the resulting solutions do not necessarily go in that direction. Nevertheless, there are solutions and design recommendations that are uncannily attuned to a use of resources similar to what Ecodesign methods set out to achieve.

In the literature there has never been a careful analysis of how inherently green is the TRIZ methodology; under which conditions it can be interpreted in this way; and which of the many TRIZ tools might be considered Ecodesign tools.

3 A Comprehensive TRIZ Based Ecodesign Approach

While each tool can be in itself applied to an Ecodesign scheme, two core aspects make TRIZ and Ecodesign a good fit. Firstly, TRIZ is a methodology that separates itself from common design processes, preferring a radical approach. The entire methodology is based upon solving contradictions (performance trade-offs) rather than optimizing them. While the classical design approach works around trade-offs in order to find the best combination of design parameters, TRIZ looks over trade-offs to find new design parameters, new or unused resources, and eventually break trade-offs to gain a leap in product development through radical innovation. By finding new design parameters or pushing the designer to use what was previously overlooked, TRIZ can gain massive results, which would not be possible via a classic incremental approach. A classic example of this type of innovation process is the "Start & Stop" concept; by introducing a new parameter, *time*, a car can save more than 10 % of its energy consumption in city traffic (US Environmental protection agency-Office of transport and air quality http://www.fueleconomy.gov/). In the same way a light can save much of its energy consumption by blinking at 25–30 fps; the same frequency used in cinemas to create the effect of motion without continuous light. A classical approach would have elected to optimize the engine or the bulb or filament design; remaining confined to the existing notion of a constant working car and a non-blinking light.

A second aspect that appeals to Ecodesign is TRIZ's core philosophy: the concept of ideality. TRIZ analyzes the products and processes according to an evolution path that brings them inevitably toward a solution where the system improves its performance while shedding its negative functions, including those that are not compatible with the environment. This solution, called Ideal Final Result (IFR), requires an extreme simplification (only what really matters) that

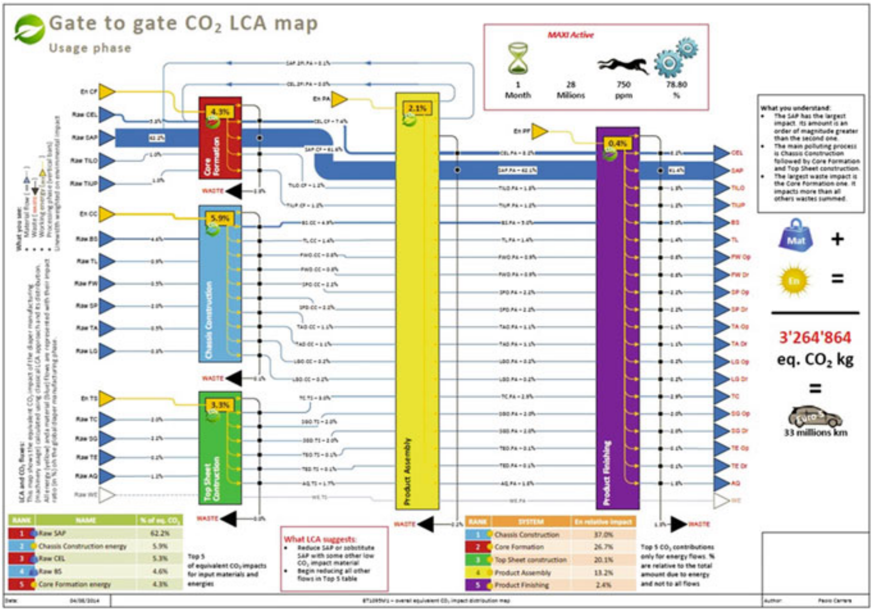

Fig. 1 i-Tree graphical interface

leads to the dematerialization of the product; such that the physical system disappears, but the function remains.

We have identified the TRIZ tools that make TRIZ and Ecodesign a successful partnership: the Laws of evolution of a technical system, Resources, Contradictions, and the 40 Inventive Principles. Each of these tools has been implement in an integrated approach called i-Tree, which aims at creating a TRIZ-based assessment and improvement tool. The main difference from available systems is the distinction of assessment criticalities and improvement criticalities, by means of IFR concept. The procedure highlights the critical product components that need to be improved, suggests customized guidelines that target specific material and energy flows and life cycle phases, and foresees possible trade-offs that are then reformulated in a set of contradictions. The entire procedure is supported by a mapping scheme (Fig. 1) that allows the user to keep track at all times of the environmental changes taking effect.

In the following, we describe the aforementioned TRIZ tools and their application within the i-Tree methodology.

4 Laws of Evolution of a Technical System

The laws of evolution of a technical systems have been introduced by Altshuller [2]. The inventor can assess the previous development of the analyzed system as well as former inventions for this system through consideration of these laws and trends of technical system evolution. They are classified into three macro categories: static, kinematic and dynamic.

Among the static laws, the first one is the *law of the completeness of the parts of the system*. It states that any working system must have four parts: the supply, the transmission, the tool (working organ) and the control element. The supply generates the needed energy, the transmission guides this energy to the tool, which ensures contact with the outside world (processed object), and the control element makes the system adaptable. Of the four, the control element is where innovation can make the biggest leap. The evolution of a system is often tied to the evolution of its control. In particular, products and processes with a low level of evolution present a control that acts mainly on the supply and the transmission. By introducing a control on the tool the entire system can evolve far beyond the original concept, surging to a substantial saving of resources and consequently reducing the environmental impact. For example, think of a chemical sterilizing agent that needs to be pumped into the product in order to sterilize it. The system control would act on the supply by regulating the pressure of the tank; on the transmission by regulating the flow of the sterilizing agent across the output orifice; and on the tool by regulating its viscosity, its temperature, and its turbulence. A further development would conceive a control on the tool, which would allow the characteristics of the sterilizing agent to change locally, only when in contact with bacteria.

The kinematic laws explain energy efficiency through a coordinated development between the different parts that make up a system. In this group of laws, TRIZ outlines the steps toward ideality and the dematerialization of the product, which can be translated into the concept of *zero impact*. The evolution of the answering machine is a good example. The product was eventually dematerialized into a service that is now provided without the need for a dedicated system.

Finally, the dynamic laws explain how the evolution of a product leads toward solutions where the tool works the object with ever-increasing efficiency, thanks to an increasingly smaller scale of physical interaction (macro to micro) and the synergic implementation of different physical effects.

The real limit of the evolution laws lies in their generality, which limits their correct interpretation to those that are less than experts of the tool.

4.1 Laws of Evolution in i-Tree

Environmental criticalities are often confused with the relative impact of each material or energy flow. While this is an important information, it does not capture the potential improvement behind each flow. In many instances, the most impacting component is vital to the product function and has already achieved a high degree of efficiency. Thus, the improvement effort could be misplaced if targeted at reducing the most impacting flow, without considering the improvement potential to be gained by such an effort. In order to discriminate between LCA (Life Cycle Analysis) criticalities (i.e., how impacting each flow is with respect to the overall impact) and eco-improvement criticalities (i.e. how much environmental impact is likely to be saved), in [17] we propose a criticalities identification scheme, based on TRIZ's law of system ideality: the Ideal Final Result (IFR). The IFR is used to identify the theoretical ideal result of each flow. By combining IFR with a database search of the compatible alternatives in material and manufacturing processes, it is possible to define a measure of the theoretical improvement range of each component. As for the other laws, they were implemented as broad recommendations within a set of guidelines specific for Ecodesign.

5 TRIZ Resources

When thinking of resources, one would automatically think about the materials that make up the product. A more in depth view will highlight the energy consumed during either the product use or its manufacturing. These are the common concepts of LCA resources. TRIZ resources is a broader concept which encompasses many resources which are generally not visible, thought of, or even logical. Some are paid for, such as electricity or heat, and other ones are free, such as air or gravitational pull. The TRIZ concept of resources is wider than the environmental concept of resources: "*Resources are everything that remains idle in the technical system and its environment*" (Salamatov). Special attention is given to those resources that are commonly thought as negative (though the concept of a negative resource is an oxymoron) and that are either avoided, or effort is given to reduce them. TRIZ on the contrary tries to use these resources and transform them into something useful. Thanks to this principle, designers were able to invent the turbocharger, a solution for which the hot exhaust gases, aggressive chemicals, and unburned gasoline are not seen as waste, but as fuel at zero cost to be further exploited!

Clearly, the concept of fully using the available resources is a key principle of Ecodesign, because it is a direct measure of the efficiency of a system.

5.1 Resources in i-Tree

The concept of TRIZ resources has been implemented in a set of guidelines. Through these guidelines, the designer is pushed to find new resources by changing the way he thinks about the product. For example by changing a property from rigid to elastic, or something that is symmetric to an asymmetry. Some guidelines even suggest ways to turn a negative resource into a positive. For instance by reusing the packaging materials, a source of waste, as part of the product, or by reusing dissipated energy to achieve a new beneficial function (think of cogeneration). Resources were also implemented in a material, process, and transport substitution scheme that guides the user in finding new resources to achieve the main product function or sub function.

6 Contradictions

At the heart of the TRIZ methodology are the contradictions. Contradictions are a way to study trade-offs in order to break them, rather than optimize them. Physical and Technical Contradictions represent the most precise way to formulate an inventive problem. They provide a clear indication of which direction should be taken and which parameters have to be used to model possible solutions. A contradiction exists in a system whenever to improve one of the system parameters, another one deteriorates. For example, if we attempt to make a product lighter by making it thinner, it also gets weaker. Instead of searching for compromise with an intermediate thickness, the Separation Principles and the 40 Inventive Principles (see Sect. 7), help the user to visualize where and when the thickness should be high or low in order to have a product which is both light and strong.

With the growing interest in the environmental footprint of a product, designers have to account for manufacturing, use and disposal, from the first stages of development. However, there is no safe action that guarantees only positive effects throughout the entire life cycle. The benefit of any alteration can only be gauged by weighing all positive effects against the negative ones. This mechanism contributes to a trial and error approach that searches for the best trade-off, rather than highlight and eliminate the negative effects brought about by the life cycle alteration.

Furthermore, trade-offs are not limited to life cycle stages, but can arise as tradeoffs between different environmental indicators. For example, changing one of the product materials can affect in diverging ways different environmental indicators, like: Global Warming, Water Acidification, Resources Depletion, etc.

6.1 Contradictions in i-Tree

In order to anticipate and possibly avoid the trade-offs arising from Eco-improvement, in [18] we propose a collection of the most common Ecodesign trade-offs and a way to anticipate them. A prompter (integrated inside an LCA graphic mapping) alerts the designer of any possible negative effect that might result from the proposed eco-improvement action, and defines a contradiction. The control parameter is usually a result of a chosen Eco-guideline (see Sect. 7) that targets a specific product aspect. Contradictions offer a new approach to Ecodesign; instead of optimizing the product life cycle, TRIZ gives the designer the means to anticipate trade-offs and formulate them as contradictions. This empowers the designer to use TRIZ's Separation Principles and 40 Inventive Principles to solve such contradictions and develop a possibly revolutionary product.

7 TRIZ 40 Inventive Principles

The 40 Principles are solution triggers, very general ideas of how to solve a contradiction. They are the easiest TRIZ tool to use, and the one most likely to give good solutions fairly easily and quickly. They have been derived by Altshuller from the extensive analysis of world patents, which led to identifying the total number of ways (40) the world has found to solve contradictions. Examples of the 40 principles are: *Change the shape or properties of an object from symmetrical to asymmetrical (principle 4, Asymmetry), Cause an object to oscillate or vibrate (principle 18, Mechanical Vibration),* or *Instead of continuous action, use periodic or pulsating actions (principle 19, Periodic Action).*

The inventive principles were not designed for Ecodesign. In fact, one might say that they are *criteria-neutral*, in the way that they can be applied to a wide variety of performance criteria, whenever there is a conflict between two parameters (a contradiction). However, not all are pertinent to Ecodesign.

7.1 40 Inventive Principles in i-Tree

By redefining the 40 inventive principles for an Ecodesign approach, in [19] Russo et al. devised a set of specific guidelines that suggest ways and tools to improve the environmental impact of a chosen material or energy flow. Thanks to the inventive principles, eco-guidelines can be very specific to the type of flow and life cycle phase. Different guidelines address the improvement of different types of flows, and each guideline is tailored to the specific LCA phase where the flow stems. In i-Tree the principles have been integrated in very specific guidelines that clearly specify what the goal is, on which element to act, and contextualize the inventive principle in order to suggest the user which of the available parameters to act upon. For example in the case of a hair dryer, if i-Tree or LCA indicates that the most critical factor is the power consumption during use, the guideline will suggest "Replace continuous action with periodic or pulsating actions and then with resonant action. Use only when action is really needed (*start and stop*)." The dynamics principle will suggest varying the intensity of the airflow according to the state of hair drying, and prompt the designer to lower the airflow when the hairdryer is pointed at areas that do not require drying. The remaining set of principles will push the designer to imagine a hairdryer that delivers air only when needed, and only where it is needed; to the benefit of the environmental impact.

8 Conclusions

The TRIZ methodology is a well established and proven problem solving tool, which only recently was introduced to the Ecodesign scene. By studying the available literature, combined with our own experience applying TRIZ to Ecodesign, we try to answer the question: "*Is TRIZ an Ecodesign method?*"

The core concepts of Ideality and Contradictions have proven to be readily applicable to eco-improvement, while TRIZ's ability to find new parameters and resources may incite new ways to tailor the eco-assessment output for the improvement phase. However, TRIZ was not developed for Ecodesign and some of its tools can be counterproductive if applied blindly. The 40 inventive principles, for instance, often lead to solutions hard to engineer or manufacture, resulting in a worsening of the environmental impacts. Even the contradictions are very effective when there is a single trade-off, but fall short when there is a network of parameters that influence the entire product life cycle. TRIZ is not an Ecodesign method, then. However, its core principle of evolving a product toward a higher level of efficiency (and to a higher degree of ideality) leads eventually to more sustainable products. Thus, it is the opinion of the authors that rather than adapting TRIZ to an Ecodesign approach, it would be preferable to create a new methodology, based on these principles and a dedicated implementation of some of TRIZ tools.

i-Tree is an example of said logic; creating an Ecodesign scheme with an eco-improvement phase largely based on the TRIZ methodology. The procedure highlights the critical product components that need to be improved, suggests customized guidelines that target specific flows and life cycle phases, and foresees possible trade-offs that may arise. TRIZ tools have been diluted inside the methodology to keep the original principles while adapting the mechanisms to the needs of Ecodesign.

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An Integrated Eco-Design Decision Making Tool

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Abstract The application of an integrated eco-design decision making tool is presented as a case study considering the design of an office chair base. This study brings together the analysis of factors relating to manufacturing processes, product usage and end-of-life strategy to demonstrate the operation of an eco-design case-based reasoning tool. This is shown to meet the requirement of the data storage, retrieval and re-use. A framework is provided to facilitate the application of sustainability criteria in the early design phase in a context with which designers are familiar. Such consideration can be made more understandable and relevant as more information is added. This makes all aspects of the process more rewarding for the participants and increases considerations of sustainability.

Keywords Sustainable product development · Quality function deployment · Life cycle assessment · Eco-design process

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1 Introduction

The integrated eco-design decision making (IEDM) methodology provides a method for improving product sustainability. Current eco-design strategies are not intended to provide the in depth assessments required to improve designs. They often lack quantitative information and do not provide direct guidance to product engineers. The IEDM applies environmental considerations across three stages of product development. The first stage is the life cycle assessment (LCA), which is used to identify critical areas in which the product's environmental performance can be improved. Although existing LCA tools provide valuable design information they do not generally provide guidance on how improvements can be achieved [1, 2]. They are not iterative and lack the required level of interaction to support designers with improvement strategies. The results of the LCA are then analysed in the second stage using an eco-design process (Eco-Process) model [3]. This model identifies environmental concerns relating to the manufacturing process, product use, and end-of-life (EOL) strategy. These concerns are then addressed within the third stage, which uses an ecological house of quality (Eco-HoQ) embedded in an ecological quality function deployment (Eco-QFD) process. The reasons for such an innovation were drawn from considerations of current approaches. Generally these can consider aspects of sustainability as and when they are identified by customers or designers [4]. This process is however rather haphazard. What is required is a systematic consideration of sustainability in an organised manner [5]. An eco-design case-based reasoning (Eco-CBR) tool is the fourth element. Previous applications of CBR to sustainable product development include the development of the communication and decision support environment [6]. This is an application of CBR which can be deployed to support concurrent product development. It proposed a hybrid method to determine recycling strategies. CBR can also act as a knowledge depository to support design functions [7]. A method for evaluating remanufacturing processes to support the integration of economic and environmental cost models has been proposed [8]. An approach to LCA using CBR for the eco-design of products has been detailed [9]. A later CBR approach allows designers to consider the indications given by established eco-design guidelines [10]. Most recently research on CBR has produced a recursive case-based reasoning method integrating industrial standards [11].

Although previous researchers have considered aspects of sustainable product development, they have not combined the main factors in sustainability, which are the environmental, economic, and social factors. The aim of the current study thus is to provide a platform for considering all of these factors by integrating eco-design features to propose reliable solutions to the new problem of product design. This study uses the Eco-CBR tool by integrating the QFD method to store all the product design knowledge in the library of cases. This allows a designer to quickly evaluate the new product design case by finding similar cases in the library.

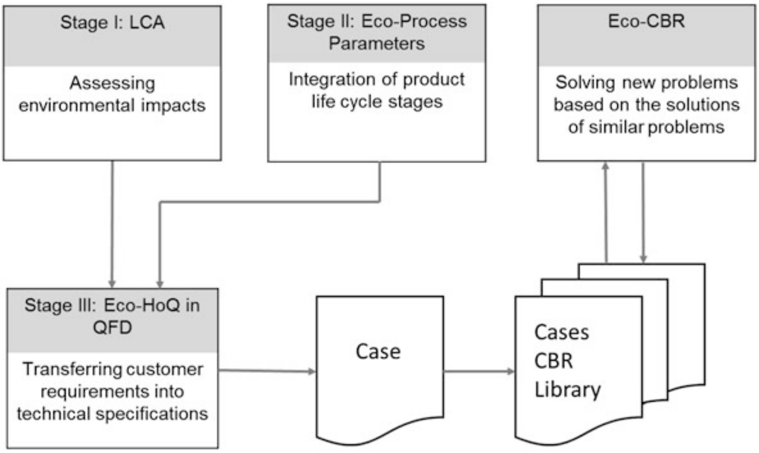

Fig. 1 The integrated eco-design decision making (*IEDM*) tool

2 The Integrated Eco-Design Decision Making Tool

The Eco-CBR is an intuitive decision support tool that applies environmental considerations across three stages of product design, as shown in Fig. 1. These stages provide an output of product information that can be stored, retrieved and re-used using the Eco-CBR tool [12, 13]. It is demonstrated in this case study of a five-pointed office chair base. Versions of this made of nylon and aluminium alloy conforming with the standard specification for performance requirements and tests [14].

2.1 Stage 1: The Life Cycle Analysis

The first stage of the IEDM tool was to complete the LCA to determine and compare the attributes of the office chair base manufactured using two different materials, nylon and aluminium alloy. The differences associated with the use of the aluminium are shown in Table 1: the environmental impact is high with an increase in carbon footprint (146 %), air acidification (834 %), water eutrophication (108.3), and total energy consumed (94 %).

2.2 Stage 2: The Eco-Process Model

The results obtained from Stage I (LCA) were then incorporated into Stage II (Eco-Process model). Tables 2 and 3 show the input parameters that were used in

Table 1 Environmental impact of office chair base: nylon versus aluminium alloy

Criteria	Nylon	Aluminium alloy
Material	Nylon 101	Alloy 1060
Type of manufacturing process	Injection moulding	Die casting
Manufacturing region	Europe	Europe
Use region	Europe	Europe
Transportation	Truck	Truck
Weight (kg)	1.287	3.023
Distance (km)	2000	2000
Recycle rate at EOL (%)	100 %	100 %
Carbon footprint	**kg CO_2**	**kg CO_2**
Material	77.43	192.06
Manufacturing	6.86	16.14
Use	0.00	0.00
Transportation	0.61	1.43
End-of-life	0.00	0.00
Total	**84.9**	**209.63**
Water eutrophication	**kg PO_4**	**kg PO_4**
Material	0.021	0.04
Manufacturing	0.002	0.01
Use	0.00	0.00
Transportation	0.001	0.00
End-of-life	0.00	0.00
Total	**0.024**	**0.05**
Air acidification	**kg SO_2**	**kg SO_2**
Material	0.103	1.30
Manufacturing	0.046	0.11
Use	0.00	0.00
Transportation	0.003	0.01
End-of-life	0.00	0.00
Total	**0.152**	**1.42**
Energy consumed	**MJ**	**MJ**
Material	1262.76	2389.99
Manufacturing	130.63	307.52
Use	0.00	0.00
Transportation	8.99	21.11
End-of-life	0.00	0.00
Total	**1402.38**	**2718.62**

Table 2 List of parameters for the quality characteristics (QCs)

Quality characteristics (QCs)	Attributes
Weight	Material usage, product use, transport, EOL product
Volume of product	Product durability, potential to reuse, potential to recycle, potential for remanufacturing, landfill disposal, incineration
Number of parts	
Number of materials	
Product durability	
Product life span	
Carbon footprint	Transportation and manufacturing region, resources, material usage, potential to reuse, potential to recycle, product usage, potential for remanufacturing, landfill disposal, incineration
Water eutrophication	
Air acidification	
Total energy consumed	
Manufacturing region	Easy to transport and retain, distance, product use
Transportation	
Rate of recycled materials	Number of materials, potential to recycle
Easy to disassemble	Number of parts, potential to reuse
Easy to clean	Number of parts, potential to reuse

Table 3 List of parameters for the demanded qualities (DQs)

Demanded qualities (DQs)	Attributes
Less material usage	Number of materials, weight, number of parts, production volume, product durability, less environmental impact, transportation, recycling rate
Easy to process and assemble	
Easy to transport and retain	
Low environmental cost	Weight of material, rate of virgin material, rate of recycled material, number of materials, production volume, design durability, product lifespan, potential to reuse, recycle, for remanufacturing
Low production cost	
Environmentally smarter	
Potential to recycle	Number of parts, easy to disassemble and clean, less environmental impact
Potential to reuse	
Safe to landfill	
Safe to incinerate	

the Eco-HoQ in Stage III (Eco-QFD). These parameters come together with cross-referencing attributes from the Eco-Process model.

2.3 Stage 3: The Eco-House of Quality

The LCA results from Stage I and the relationships between eco-design parameters in Stage II were integrated into the Eco-HoQ. As shown in Fig. 2 this extra "house" can capture and manage sustainability considerations in a single place. In doing so it acts as a master platform for analysing the contributions of the sustainable product design parameters retrieved from the Eco-QFD phases. The addition of the Eco-HOQ brings sustainability to the centre of the considerations. When enacted the Eco-HOQ will capture and make available important information. This information will be accessed using the tools developed by this research.

By considering sustainability in all aspects of product design and manufacture, it should be possible to make more appropriate decisions regarding design

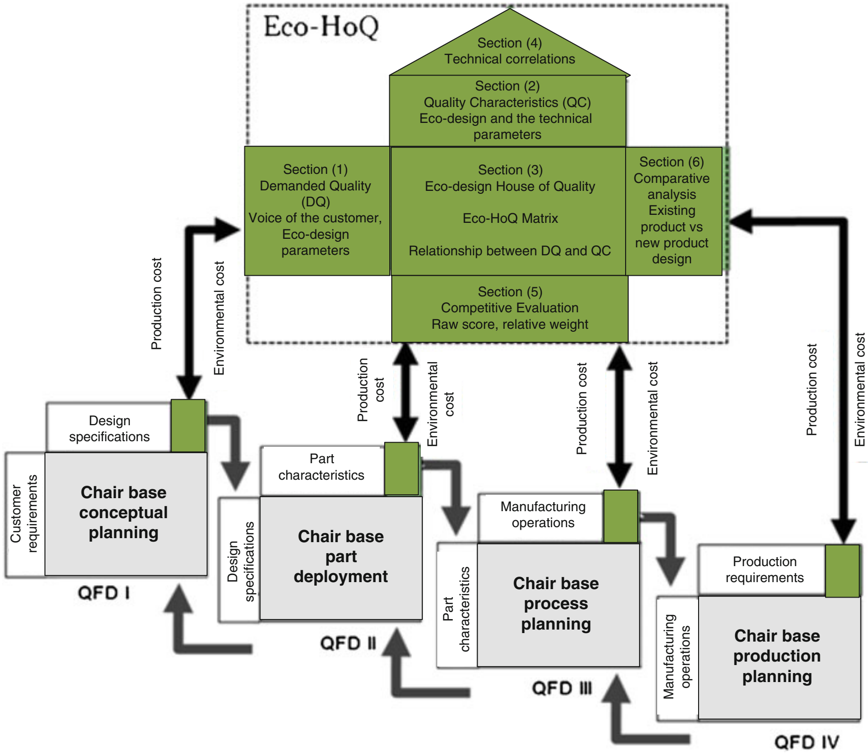

Fig. 2 Conceptual model of the EcoHoQ within an enhanced QFD process

Technical engineering: Nylon / Sustainability Cost	Weight	Economic				Environmental						Social				
		Purchase cost	Manufacturing cost	Transportation cost	End-of-life cost	Rate of recycled materials	Manufacturing region	Totalenergy consumed	Carbon footprint	Water eutrophication	Air acidification	Easier to use	Better value for money	Reliability	Greater adaptability	Easier to service
Chair base- Body weight up to 150 kg	19.7	●	●	●	●	●	●	●	●	●	●	●	●	●		
5 point unit without castors	18.7	●	●	●	●	●	●	●	●	●	●	●	●		●	●
Accepts 11mm diameter clircliped castor	9.0	●	●	●	●	●	●	●	●	●	●	●			●	●
570mm diameter for the circle chair base	11.4	●	●	●	●	●	●	●	●	●	●	●	●		●	●
Less weight	9.2	●	●	●	●	●	●	●	●	●	●	●	●			●
Raw score		612	612	612	612	611.8	612	612	612	612	612	612	531	178	352	434
Nylon (Average value)		6.12				6.12						4.21				
Aluminium alloy (Average value)		5.65				3.38						4.08				
Alternative design (Aluminium alloy)		↑	-7.71%			↑	-44.81%					↓	-3.2%			

Technical engineering: Aluminium alloys / Sustainability Cost	Weight	Economic				Environmental						Social				
		Purchase cost	Manufacturing cost	Transportation cost	End-of-life cost	Rate of recycled materials	Manufacturing region	Totalenergy consumed	Carbon footprint	Water eutrophication	Air acidification	Easier to use	Better value for money	Reliability	Greater adaptability	Easier to service
Chair base- Body weight up to 150 kg	18.2	●	●	△	●	●	●	△	△	△	△	●	●	●		
5 point unit without castors	19.0	●	●	●	●	●	●	△	△	△	△	●	●		●	●
Accepts 11mm diameter clircliped castor	9.7	●	●	●	●	●	●	△	△	△	△	●			●	●
570mm diameter for the circle chair base	12.3	●	●	●	●	●	●	△	△	△	△	●	●		●	●
Less weight	8.3	△	△	△	●	●	●	△	△	△	△	●	△			△
Score		575	575	502	608	607.9	608	203	203	203	203	608	487	163	369	411
Aluminium alloy (Average value)		5.65				3.38						4.08				

Fig. 3 Eco-HoQ model summary: sustainability categories

requirements such that extra costs can be reduced or even removed. In this way, more sustainable products need not always be associated with higher costs.

All of the eco-design parameters were assigned a weighting factor to establish the relationship between demanded qualities (DQ) and quality characteristics (QC). The different weighting factors in each group are highlighted with a red box in Fig. 3. The parameters in the economic category were: purchase cost, manufacturing cost, transportation cost, and end-of-life cost. They were retrieved from Eco-QFD Phases I and II. For the environmental category, the parameters were: rate of recycled materials, number of materials, manufacturing region, carbon footprint, water eutrophication, and air acidification; these were derived from the Eco-QFD phases. The last category is social (customer requirements), which had the parameters: easier to use, better value for money, reliability, greater adaptability, and easier to service. All these parameters were derived from Eco-QFD Phase I.

The analysis shows that the economic cost and environmental cost for the aluminium alloy product are higher than the chair base made with nylon, with respective values of −7.7 and −44.8 %. Meanwhile, for the social (customer requirements) category, the chair base made with aluminium alloy received slightly lower customer satisfaction (3.2 %) than the one made with nylon.

2.4 Stage 4: The Eco-CBR Tool

The Eco-CBR was developed to generate solutions for new product designs by finding similarities with previous design cases held in the Eco-CBR library, which designers can learn from. To do this the Eco-CBR method supports and maintains an organised case library. It aids in solving product design problems by finding similarities with previous cases; the experiences from these similar cases can then be used to generate and assess design solutions. The case consists of two sections: the problem and the solution. The features used in this case are a mix of generic and specific features. Generic is used in the sense that they apply to a wide range of products. Specific in the sense that these features are product based. Several types of materials were selected on the basis of existing chair bases in the market. From this study, 24 cases were created and stored.

2.5 New Case Development

A new case for evaluation using the Eco-CBR was proposed using attributes classified in four groups, shown in Fig. 4. The features for the design dimensions group were specifically designed for the chair base. The new case used different values than existing cases: material recycled content was assumed the be 50 % and used in this new case to give same strength as existing product; material cost was reduced to £0.0026 per gram because of the recycled content; design dimensions were decreased by 5 % from the current design to reduce its weight. This reduction was achieved by reducing the thickness of the section used. For the purposes of this study the minimum safe load was set as 2.5 kN in order to achieve the standard of office furniture. To find a solution to the new case a search of similarities from existing cases in the Eco-CBR library was conducted. The process of retrieving and reusing solutions from existing cases helps the designer to revise and apply domain knowledge to the new case. The next step searched for similarities between the new case and existing cases in the library.

There are many ways of measuring similarity and different approaches are appropriate for different case representations. In this study, a local similarity measure is usually defined for each attribute and a global similarity measure is computed as a weighted average of the local similarities. The weights assigned to case attributes allow them to have varying degrees of importance and may be selected by a domain expert or user. The Eco-CBR tool retrieves the cases that are maximally similar to the new case by computing the similarity of the new case to

NEW CASE (PROBLEM):

Transportation
Origin: Europe
Destination: Europe
Transport: Truck
Distance: 2000 km
Material and manufacturing process
Material: Nylon 101
Weight: 1223 gram
Manufacturing process: Injection moulded
Material recycled content: 50%
Material cost: £0.0026 per gram
Production volume: 50,000
EOL
Recycled: 100%
Incinerated: 0
Landfill: 0
Design dimensions
Diameter castor (D1): 11 mm
Height from the top base (D2): 130 mm
Diameter for the base (D3): 570 mm

SOLUTION: ?

Fig. 4 Input values for the new case

every case in the case-based library. The results were based on the highest similarities found in the search process, with similarity "0.95" for the transportation group, "0.75" for the material and manufacturing group, "1.00" for the EOL group, and "0.97" for the design group.

The next stage is applying previous experiences to the new case. If the new case is exactly like the existing case in the library, then the existing solution is copied to the new case. However, if the new case is different the previous case or cases must be adapted. The recommended solutions from the Eco-CBR library need to be revised and adjusted to solve the new case. In the Eco-CBR method, the process of adaptation is an important step, as it translates the retrieved solutions for the current problem (new case). When a designer is satisfied with the solutions, the case will be retained, and the library updated. This new case can be accessed in the future, allowing for the reuse of proven solutions.

Five performance criteria were applied to test the solution: environmental impact, cost estimation, design dimension assessment, customer requirements and Eco-QFD indicators. Table 4 shows the potential for improvement associated with the adoption of the new chair base by comparing with the existing product. Many improvements were observed from the changes of the reduction of material usage, and the use of material recycled content. It is worth noting that this solution was retrieved from an existing case that has 0 % recycled content. In the new case, the recycled content for the material is 50 %. Therefore, the designer must revise this retrieved data by reducing values for the carbon footprint, energy, air acidification,

Table 4 Environmental impact of the new design versus existing design (per unit)

Criteria	Existing design	New design
Material	Nylon 101	Nylon 101
Types of manufacturing process	Injection moulding	Injection moulding
Manufacturing region	Europe	Europe
Use region	Europe	Europe
Transportation	Truck	Truck
Weight (g)	1287	**1223**
Recycle content in product (%)	0 %	**50 %**
Recycle rate at EOL product (%)	100 %	100 %
Economic cost (£)	9.26	6.56
Carbon footprint (kg CO2)	84.90	**46.16**
Water eutrophication (kg PO4)	0.02	**0.014**
Air acidification (kg SO2)	0.15	**0.10**
Total energy consumed (MJ)	1402.38	**771.00**

and water eutrophication for the product. The improvements result in decreasing the carbon footprint (84 %), water eutrophication (43 %), air acidification (50 %), and total energy consumed (82 %). Additionally, the economic cost has also decreased by 41 % due to the above changes.

3 Discussion

The IEDM framework proposed applies environmental considerations across three stages of product development; LCA, Eco-Process and Eco-QFD. It was designed to embed sustainability and add functions to the existing QFD process. The Eco-HOQ was engineered to add sustainability consideration at each stage of QFD process. The need to store and provide access to the information generated was seen to be vital. The CBR method was therefore integrated into the framework with the aim of enabling information capture, re-use and optimisation. The resulting framework was designed to be intuitive and flexible in its application. It allows the attainment of identified eco-design objectives by including environmental considerations in every phase of the design process. The process starts with the inclusion of a sustainability performance evaluation among the criteria in the configuration design phase. The sustainability is central to considerations producing possible design alternatives of a product. The evaluation of the generated design alternatives includes reference to and use of sustainability criteria. The framework, its tools and methods will support a user-friendly approach that can be adopted in the working environment of product designers. This is demonstrated here in the case study but is intended to be applicable across a wider sector of design activities.

4 Conclusions

This research used case-based reasoning references to search for design parameters in order to achieve sustainable solutions to design problems. Eco-QFD was expanded to guide the search of competitive products using Eco-CBR to meet quantitative targets and to increase knowledge of sustainable product designs. The application of the entire IEDM framework, including the Eco-HoQ, Eco-QFD, and complementary Eco-CBR, is demonstrated in the case study reporting the re-design an office chair base. The case studies demonstrate the effectiveness of these tools when assessing a product's sustainability, even when its design is altered. In addition, this methodology provides a complete view of the environmental performance and economic cost of these products over their entire life cycles in conjunction with an assessment of customer requirements.

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A Bridge Between CAD and LCA to Optimise the Life Cycle Inventory Phase

Marco Mengarelli, Sara Cortesi, Patrizia Buttol, Marco Marconi and Francesca Reale

Abstract Having environmental indications such as those provided by Life Cycle Assessment (LCA), while designing a product would reduce the time required by the trial-and-error approach resulting from environmental checks only at the end of the process, directing the development towards more sustainable solutions from the beginning. To achieve this, the design and environmental analysis should be more integrated, as well as the respective tools. The project idea discussed in this paper aims to overcome this barrier by defining an XML (eXtensible Markup Language) structure designed to carry Life Cycle Inventory data from Computer Aided Design (CAD) tools to Life Cycle Assessment tool. The idea is to exploit overlapping data between the CAD system and LCA instruments, which are currently not being considered. This process will contribute to the reduction of time required for data input and the amount of mistakes.

Keywords LCA · Eco-design · CAD · LCI

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1 Introduction

Life cycle assessment (LCA) is a methodology to evaluate the potential environmental impacts of a product or service across its life cycle, that is to say considering the pre-manufacturing, manufacturing, distribution, use and end-of-life phases.

The interest in this methodology, and in life cycle thinking in general, is growing since the 1990s, and is reflected in international actions such as the Life Cycle Initiative [1], jointly organized by UNEP and SETAC, and the Single Market for Green Products Initiative [2], promoted by the European Commission.

Adopting a life cycle approach promotes awareness about the influence of single choices on larger systems, the consideration of a longer time scenario, the improvement of a system, in relation to a defined function or need, instead of only single parts or products, and informed choices [3].

This can be true for many types of decision makers, including those involved in a design process within a manufacturing company. In that context, the LCA methodology can be useful in guiding design choices, such as the selection of materials or production processes, which can lead to the definition of a product with a lower environmental impact along its life cycle, avoiding burden shifts. The more the methodology is integrated into the design process, going along all its phases instead of being a check at the end of the main phases or at the end of the overall process, the better results can be obtained, avoiding a time-consuming trial-and-error approach and providing reliable results in a quick, operative way.

Notwithstanding the potential benefits and the international political and scientific consensus, and even if many large companies have expert teams supporting the integration of LCA into product development [4], Small and Medium Enterprises (SMEs) are still struggling in adopting LCA. Among the reasons behind this situation there are little budget and workforce to be dedicated to environmental analysis [5], lack of environmental competences and of tools dedicated to non-expert users [6], the availability of data needed to perform a Life Cycle Assessment and the amount of time required to collect them [7, 8].

Trying to overcome this last barrier, few attempts have been made to reduce the time needed to compile a Life Cycle Inventory (LCI), i.e. the collection of inputs and outputs of a system. One of the directions that has been followed is to integrate environmental screening and audit features into Computer Aided Design (CAD) modelling software (e.g. SolidWorks Sustainability by Dassault Systèmes and the MI: Materials Gateway by Granta Design), considering that part of the data required to model the life cycle of a product is already available in a CAD model and that CAD tools are widely used in manufacturing companies.

In this same direction, from 2012 to 2015 the authors collaborated within the G.EN.ESI project [9], co-financed by the European Commission within the VII Framework Programme. One of the main goals of the project was in fact the development of a software platform of interoperable tools dedicated to support more effective and efficient environmental design decision-making in SMEs in the mechatronic sector. The resulting G.EN.ESI platform integrates dedicated streamlined Life Cycle Assessment (sLCA) and Life Cycle Costing (LCC) tools with existing CAD and Product Lifecycle Management (PLM) systems.

Following the insights gained during the G.EN.ESI project working on specific tools, this paper investigates the possibility to define a general structure for the exchange of data between commercial LCA and CAD tools, in the format of an XML (eXtensible Markup Language) file. The activity aims to exploit the overlap of data in between the instruments, leading to the automatic compilation of part of the LCI, reducing the significant amount of time and possible error generation usually related to manual data input, thus helping the realization of LCA studies that support more environmentally sustainable design choices, focussing the human input on the interpretation of the results instead of on data entry.

Thus the activity would be integrated into the process leading to a complete and structured LCA, unlike what happens for other tools, where only parts of the product life cycle are considered [10–12].

Moreover, unlike what described by other papers [13], the proposed activity would not lead to a software-specific solution, i.e. strictly linked to the characteristics of one specific CAD tool, but instead it would explore the possibility of providing a basic communication structure with XML upon which a bridge in between different CAD and LCA software tools can be developed.

2 Proposed Approach

The development of a software application that acts as a bridge between design tools and LCA tools makes it easier to exploit all the relevant data included in a CAD model to build a LCI. This application should be structured in such a way to be able to perform three actions: read data from the CAD model of a product, extract and properly organize the significant information, use these data to build the inventory in an LCA tool. The focus of the present research work is on the second action, i.e. the identification of data available in a CAD model that can be useful for an LCA study and their organization in a form suitable to build an LCI.

This approach requires that both CAD and LCA retrieve information from the same database, which might be the company database, where data about materials, manufacturing processes, commercial components etc. are stored. The database could also store the related environmental data collected at the company or from the supplier. As an alternative a data matching between different databases used by the tools is needed. This latter solution does not involve the creation of a univocal company database, but allows the use of existent ones, leading to lower impact.

Figure 1 presents the steps of the proposed approach: starting from the data contained in a CAD model and from the data needed for a complete description of the life cycle of the product, the approach allows the definition of a product model that can be used to collect data from the CAD tool in a form suitable to be used/read by the LCA tool.

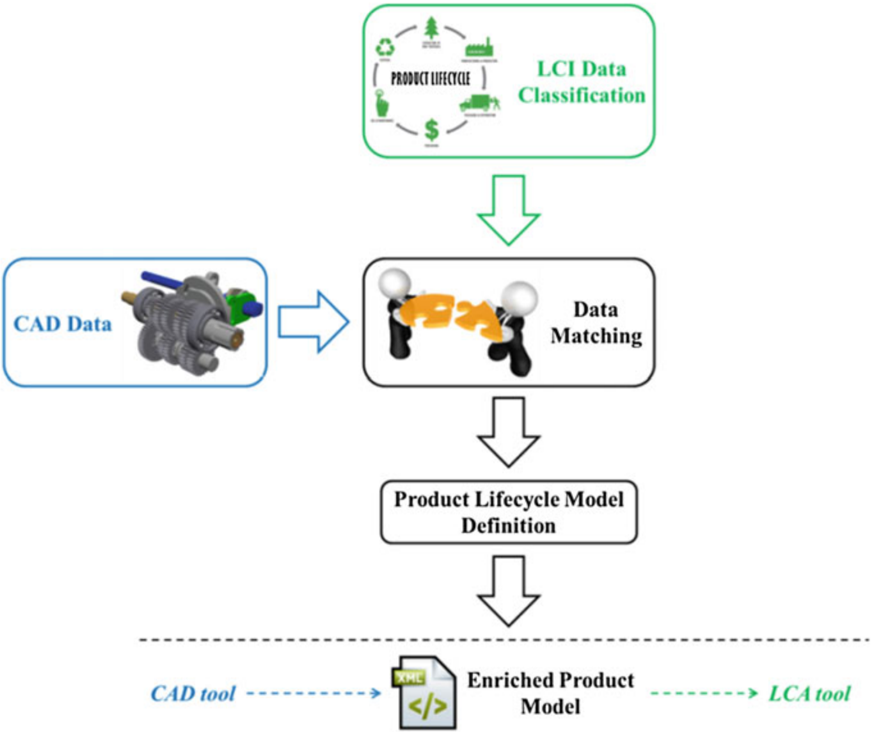

Fig. 1 Steps of the proposed approach

LCI Data Classification consists in identifying the necessary data to build the life cycle model of a generic product. All of the information is collected concerning the different life cycle phases, from material production and manufacturing to the end-of-life.

After LCI data classification, a *Data Matching* step is required. The comparison between the data necessary to build an LCI and the data available within a CAD model allows the similarity between the two different product representations to be mapped. As the LCI requires modelling the entire life cycle, more data than those available in a geometrical model are needed. In addition, some data extracted from the CAD model can be directly used (e.g. material), while some others can only be obtained on the basis of additional parameters (e.g. manufacturing processes identified from geometry, tolerance surface finishing, etc.).

The *Product Life cycle Model Definition* step consists in creating a univocal model that includes all the necessary fields to store data of a complete inventory, organized in the most appropriate and useful way. The final objective is to define an *Enriched Product Model* manageable by LCA tools, through the implementation of a dedicated bridge software application, which is out of the scope of the present work.

2.1 Data Classification and Matching

As previously discussed, some data are used both in the CAD system and in the LCI phase, but the overlap is currently not being exploited because LCA and CAD are often used at different moments and by different actors of the design process. The CAD is an important tool, used by designers along the entire product design process, with the aim to obtain a detailed virtual representation of a product. LCA tools are generally used by sustainability experts during the last phases of the design process, in order to optimize the product environmental performances. In this section, the list of data available in the CAD model which can be transferred to LCA tools is presented.

For a given system boundaries definition, all data related to the system under analysis must be inserted. Looking more into detail, in the context of this research work the reference system is a product component. LCA tools are characterized by their own customized interfaces and structures, organizing and presenting data in different ways. However, they all adopt a life cycle approach, collecting input and output of a product or system along the whole life cycle, i.e. the pre-manufacturing, manufacturing, distribution, use and end-of-life phases. In this context, only the first two phases will be considered, since in the CAD system only data referring to that part of the life cycle are elaborated.

Looking at the CAD, nowadays companies can choose between a large number of different CAD systems to create virtual product prototypes that can also be shared with other design environments such as Computer Aided Manufacturing (CAM) and Computer Aided Engineering (CAE). As a consequence, the need to create a standard to manage technical product data is relevant in order to decrease errors and misunderstanding between operators. For this purpose, an International Standard has been created to define the encoding mechanism on how to represent data according to a given schema. For more than one decade, the STEP (Standard for the Exchange of Product Model Data) format has been used for data exchange. STEP, provides a representation of product information along with the necessary mechanisms and definitions to enable product data to be exchanged. The exchange is among different computer systems and environments associated with the complete product life cycle including design, manufacture, utilization, maintenance, and disposal [14]. This kind of information can be used for different purposes. Specifically, to some extent, these data might be exploited to compile the LCI.

The STEP format has different application protocols (AP). The most used in Europe is the STEP AP214, which is characterized by a large number of information, e.g. it defines the geometry, topology, and configuration management data of solid models for mechanical parts and assemblies. The existence of a STEP file gives the possibility of extrapolating LCI related information from the CAD. From this assumption, an XML file structure could be set to store a selection of data available in current STEP files, aiming to contribute to the LCI generation.

In Fig. 2, data available in the CAD are matched with data required by the LCI in the LCA software. As previously claimed, the information is retrieved from the

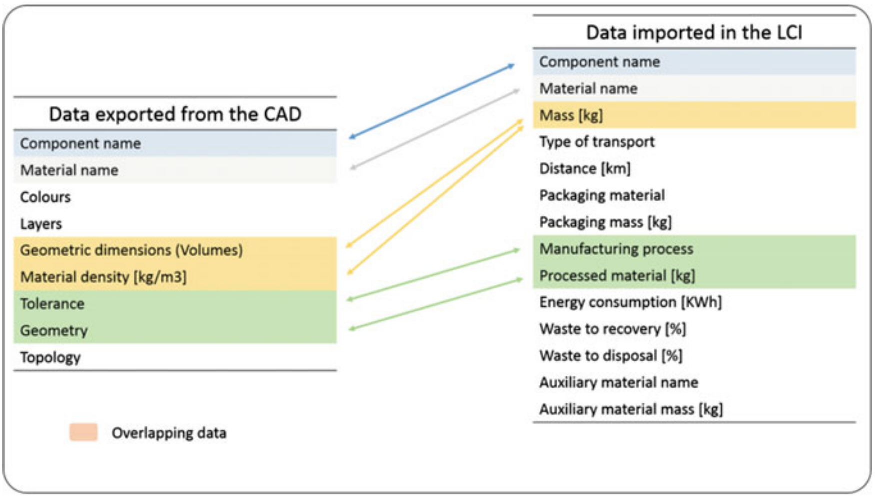

Fig. 2 Overlapping component data between the CAD system and LCI

STEP schema and thus the type of CAD is not relevant. On the LCA side instead, the information presented refers to a generic LCA software interface.

As we can see from the Fig. 2, even though more data are required by the LCI than those available in the CAD system, the integration provides a significant amount of data that could be automatically imported and input in an LCA model.

2.2 *Product Lifecycle Model Structure*

The proposed product life cycle model is based on the XML meta-language. This allows the definition of customized structures and rules to efficiently encode information which has to be interpreted by humans and machines, thus it is very suitable to model an LCI. Figure 3 illustrates the XML structure defined to model a generic product component. This represents the basic entity to build the entire product life cycle enriched model. The model is suitable for both in-house manufactured components and commercial ones (e.g. screws, electric motors, etc.). Generally, for the former category the information to complete the different fields included in the component node is available in the CAD model. Regarding commercial items, instead, some data could not be available because of the lack of the entire CAD model or part of it (e.g. material assignment). In these cases, the LCI of such components would not be automatically filled in using CAD data, but users can manually add the required information by using the bridge application. In any case the XML structure remains valid.

For each component, the proposed XML structure models the most important life cycle phases (pre-manufacturing and manufacturing, packaging and

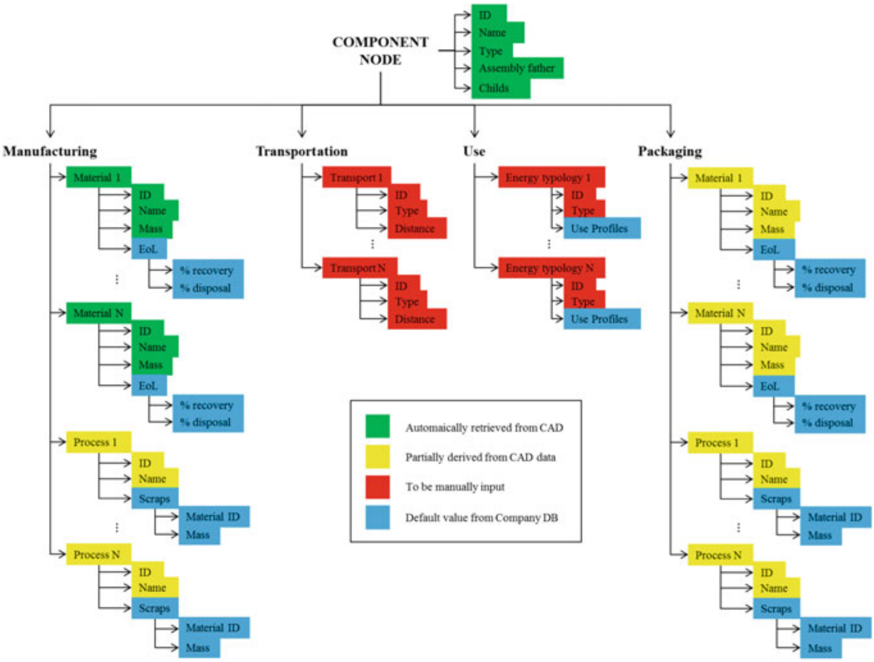

Fig. 3 XML structure

transportation, use and end-of-life). This structure is general and it may need customizations to take into account the specificity of each product (e.g. different parameters to model a manufacturing process).

A relevant quantity of the necessary information is the same managed by CAD tools (e.g. component identifiers, materials, mass, etc.), thus they can be automatically retrieved and inserted in the XML (green boxes in Fig. 3). Other data, instead, can derive from CAD, thanks to specific algorithms (yellow boxes in Fig. 3) but are not directly available. For example, the needed manufacturing processes to produce a part can be calculated on the basis of the geometric entities (surface finishing, tolerance, holes, etc.).

Some life cycle phases, as transportation or use, are not generally considered by CAD tools, so all these data have to be manually inserted in the XML to complete the inventory (red boxes in Fig. 3). However, Use Profiles, which are complex nodes containing information about each working point of energy-using components (power consumption, efficiency and working time), can be set using default values. In certain cases, these can be defined based on normative (e.g. standard use profiles for household appliances) or internal standards, derived, for example, from market surveys or users' interview.

Some information can be automatically set using default values contained in the shared Company database about materials, processes or components (blue boxes in Fig. 3). This is the case of standard values for EoL recycling of materials. Even if the EoL scenarios of materials depend on different parameters (e.g. components and products where the material is used, coupling with other materials, region where the product is disposed, etc.), companies may have sufficient information to estimate default values with an acceptable degree of accuracy [15]. So that designers can start from this pre-defined values and eventually change them if they have additional information to better estimate the needed data.

Regarding the substitution of components for maintenance during the product useful life, it is not directly taken into account within the proposed XML structure, but this problem can be easily overcome by setting that more than one occurrence of a component is needed in the LCI.

3 Preliminary Case Study

In this section, concepts and processes previously described will be applied to a case study. Currently, the passage from theory to practice still requires "manual" support since the software framework has not been created yet. However, the case study aims to clarify the scheme presented and to show the feasibility and the benefits obtained from the exchange of data between two systems.

Within the current case study, the 3D model has been created with a commercial CAD tool called Creo by PTC. The LCA has been performed by using the simplified LCA tool called eVerdEE. eVerdEE is a web-based screening Life Cycle Assessment tool for European Small and Medium sized Enterprises (SMEs) that adapts ISO 14040 requirements while offering easy-to-handle functions for less expert users [15]. Specifically, eVerdEE engages simplification at different levels. It is characterized by a user-friendly interface shaped for inexperienced users. In addition, it manages a reduced amount of elementary flows compared to commercial LCA tools. These two software represent potential instruments that fit with the presented approach.

The case study describes the creation of the LCI for a component of a domestic cooker hood, whose CAD model is available. The component is located in the lower part of the product and its functions are to protect the electronic parts and to host the filters. The first step in the procedure consists in assigning material properties to the 3D model in the CAD environment. Afterwards, other properties such as tolerances are specified once the 3D model is imported in the 2D environment. At this point this information has been set in the model therefore it is ready to be exported. An example of this step and the representation of the 3D model are shown in Fig. 4.

Following the proposed approach, the information will be exported from the CAD by using a specific application program which is able to send data to eVerdEE.

More in details, Fig. 5 represents which information will be transferred from Creo to the eVerdEE model describing the pre-manufacturing and manufacturing phases.

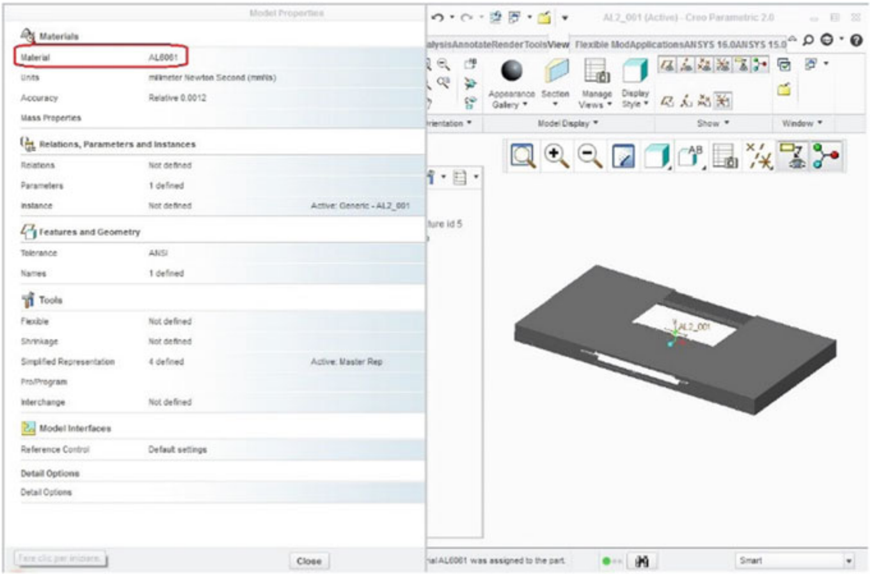

Fig. 4 Material assignment in the CAD software

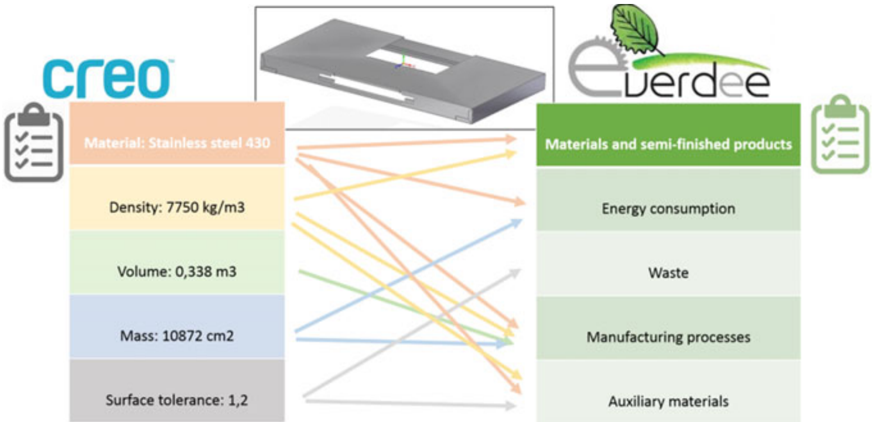

Fig. 5 Data exchange example

Information will be collected in an XML based file, with a customized structured that can be read by the LCA software. By using a specifically developed reader, eVerdEE will read the transferred information and the LCI in eVerdEE will be partially but automatically filled up with all the transferred data. In Fig. 6, a small set of information that would be automatically imported is shown. Within the proposed workflow, the user will be now able to complete the LCI stage and launch the calculation.

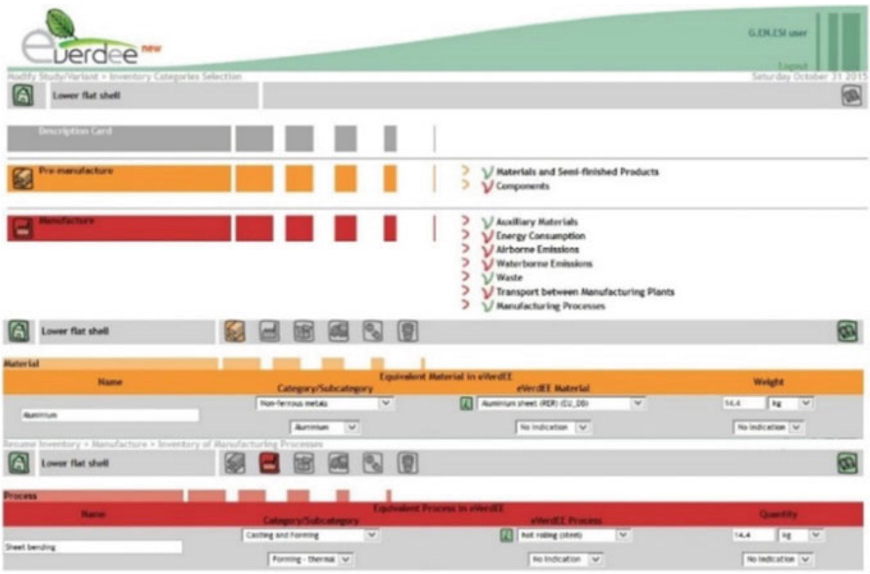

Fig. 6 eVerdEE LCI inventory

4 Conclusions and Future Steps

In the present research work, a procedure to make the LCI compilation less time-consuming and error-generating, thus supporting the integration of LCA into the design process has been presented. The idea beyond is to create a bridge between CAD and LCA in order to exploit common information and automatically compile a partial LCI. The focus of this study is on the definition of a customized XML structure, which represents the physical mean to connect CAD data and LCA data.

Even if only at a partial level, the possibility to create an LCI model by directly importing data from the CAD would boost the most demanding LCA stage and would reduce the risk of committing mistakes as data are automatically transferred. Such an approach could foster the use of LCA instruments, particularly for less experienced users and in the design environment, where it is currently not often used.

Moreover such approach enhances the concepts of repeatability and objectiveness. Despite the need of subjective choices at setting level, in order to establish the mapping rules between CAD features and LCA datasets, during application the user is systematically guided to the LCI definition. This leads to a reduction of subjectivity regarding the inventory, thus to more reliable analyses.

The practical implementation of this approach requires a software application which carries out different tasks. In particular, this tool should be able to communicate with Application Protocol Interfaces (API) from both sides.

The application should be able to use the API of the CAD tool in order to retrieve selected information. Then, an XML file, with the defined structure, needs to be created. At this point, the user should interact with this application in order to check information exported from the CAD, possibly add and/or remove parts and complete the inventory with additional information about the different life cycle phases. A user interface with a limited amount of choices should be set in order to let the user customize the import process, without leaving too many degrees of freedom to avoid complexity. Once the import phase has been completed, the application should be able to automatically pilot the LCA software, by interacting at API level, to create an LCI model with the information stored in the XML. The LCI model is created according to the mapping rules to match the CAD features with the LCA datasets. Besides the benefits already discussed, this application would ease the LCI creation step, guiding the user in the early stages of an LCA study.

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Part VIII
Invited Session 4: Redistributed Manufacturing for Resilience and Sustainability

Can Re-distributed Manufacturing and Digital Intelligence Enable a Regenerative Economy? An Integrative Literature Review

Mariale Moreno and Fiona Charnley

Abstract This paper uses an integrative literature review to explore the concept of re-distributed manufacturing and the opportunities to deliver more regenerative and resilient systems of production and consumption through the application of circular innovation. The study identified multiple similarities between the drivers of re-distributed and circular models of production and consumption that could be fostered by the use of digital intelligence. A set of criteria for redistributed manufacturing and circular innovation were developed and used to identify 33 existing case studies of consumer goods production. Case study analysis resulted in the identification of three types of re-distributed manufacturing that integrated characteristics of circular innovation. The paper concludes by describing some of the future research challenges in the transition towards re-distributed and circular models of production.

Keywords Re-distributed manufacturing (RdM) · De-centralisation · Circular economy · Digital intelligence · Consumer goods

1 Introduction

The linear production of the consumer goods industry, worth approximately USD3.2 trillion, has remained largely unchanged and places emphasis on mass manufacture through multi-national corporations and globally dispersed supply chains with 80 % of materials ultimately ending up in landfills. Consumer goods production, has created a void between the manufacturer and end user, limiting the

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opportunity for personalisation, up scaling of local enterprise and the development of user-driven products that are tuned to the requirements of local markets. It is proposed that Re-distributed Manufacturing (RdM) enables a connected, localised and inclusive model of consumer goods production and consumption that is driven by the exponential growth and embedded value of big data.

The EPSRC-ESRC[1] funded Network in Re-distributed Manufacturing, Consumer Goods and Big Data (RECODE) has been created to explore the opportunities and challenges to build a research agenda associated with the application of big data in the transition towards a re-distributed manufacturing model for consumer goods. As part of this network a feasibility study on circular innovation and RdM has been conducted to explore the requirements of RdM enabled by big data to deliver de-centralised and circular models of consumer goods production and consumption.

The concepts of circular innovation and RdM are relatively new. However, there has been an increasing interest for the last ten years from different scholars and research consultancies [1–9] in the topic of circular innovation, and its implications mainly in China, and most recently in the developed world pronominally in Europe. The interest in RdM is even more recent and there are still different descriptions and interpretations about the concept [10–15].

For the purpose of this paper, circular innovation and circular economy will be used in parallel to describe an "industrial economy that is restorative by intention and design where transformational changes through innovations are applied to decouple human wellbeing form resource use and environmental impact" [6, p. 7]. In addition, RdM will be defined as 'the shift from centralized to decentralized manufacture with the aim to create a more resilient and connected system taking advantage of digital intelligence and newly emerging technologies, to provide agile, user driven approach that will allow for personalisation and customisation of products to local markets'.

To investigate the relationship of these two concepts, this paper aims to explore, through an integrative literature review, the concept of re-distributed manufacturing and the opportunities to deliver more regenerative and resilient systems of production and consumption through the application of circular innovation. The paper starts with a review of the fundamental drivers of circular economy and RdM from which criteria, that describe the similarities and differences of both models, are identified. These criteria were then used to analyse 33 case studies of consumer goods production, which resulted in the definition of three models of RdM with circular innovation characteristics. The paper concludes by describing some of the future research challenges in the transition towards re-distributed and circular models of production.

[1]EPSRC and ESRC are part of the UK Research Council funding bodies on Engineering and Physical Sciences Research Council and Economic and Social Research Council respectively.

2 Fundamental Drivers of Circular Economy and RdM

According to Lacy and Rutqvist [9], the three fundamental drivers of the circular economy are: resource constraints, technological development and socio-economic opportunities. These drivers are not so far off from the drivers that could enable the decentralisation of manufacturing. Although, RdM is not primarily driven by a need to address sustainability issues, it is predicted that the introduction of digital intelligence and connected objects would potentially reduce resource use and will enable circular systems [16]. Emerging technologies such as automation and robotics, big data analytics, the Internet of Things (IoT), additive manufacturing, cloud computing, mobile technologies, social networks, and modular design amongst others support the transition towards a more connected decentralised manufacturing systems [14]. A clear strategic vision of the capabilities of digital intelligence to enable RdM is the German vision of Industry 4.0. INDUSTRIE 4.0 is described as the "paradigm shift from 'centralised' to 'decentralised' production made possible by technological advances which constitute a reversal of conventional production process logic" [17, p. 5]. It is foreseeing that Industry 4.0, will transform the design, manufacture, operation, and service of products as well as the way consumption is done due to the elevate mass customisation that will be enabled [18].

To enable RdM in the consumer goods sector there is clear evidence of the opportunities that could be enabled by the application of digital intelligence. To relate these opportunities to the circular economy is important to analyse the environmental and socio-economic benefits that their application in the consumer goods sector could bring. In terms of environmental benefits, digital intelligence will support new business models to effectively manage resources within markets, ensure waste is eliminated and monetized [9], and support selling products as services which will enable keeping products in longer use to minimise waste and resources [3, 9]. In addition, if technologies such as additive manufacturing are intentionally designed to reduce the amount of materials required in production, it could contribute to reduce the use of resources and waste [19]. Emissions from transportation could be also minimised by increased flexibility and greater control provided by the use of digital intelligence. Shifting to regional and localised manufacturing increases the potential to minimise transport and internalise material flows by being closer to the consumer [19].

To better understand the socio-economic benefits, it would require an understanding of where real value could be created by addressing a set of system issues, and enabling new business models for the consumer goods sector [20]. For example, the use of digital intelligence can improve productivity and production efficiency. It is predicted that Industry 4.0 will be embraced by more companies, boosting German productivity by €90 billion to €150 billion in the next five to ten years [17]. In addition, it is evident that companies are constantly constrained by risks resulting from climate change, currency fluctuation and resource security affecting global supply chains. Thus, digital intelligence can be useful to run more resource-productive supply chains by optimising operations, setting in place an optimised inventory, and predicting maintenance [20]. Take for example new technologies that allow trace and return systems. These systems are enabled by digital and physical technologies that allow products to be traced and transferred from end users to the manufacturer or a third party, keeping track and control of assets. By using real time data, it would be more cost-effective for companies to monitor, predict and prevent breakdowns of products and at the same time enable collection for service repair, recover, reuse, or refurbish [20]. With advanced recycling technologies, trace and return systems will also drive new opportunities to collect, process, and reuse materials, leading to more interconnected markets in which outputs are used across industries as inputs [9].

Digital intelligence will also create added value through high customisation of products and services. Mass customisation is foreseen as a dominant model for satisfying varying consumer needs [18]. This will not just drive revenue growth as consumers would be prepared to pay a premium up to 10 % for personalised goods, but also will enable closer relationships between companies and the communities they operate within [10]. Consumers would gain more value through convenience, time saving, and more attractive customised promotions [18]. High customisation will also provide a significant breakthrough in health and wellbeing. Digital intelligence is already being used to monitor and treat illness, and it is foreseeing that it will improve wellness by using data generated by wearable technologies to track and modify diet and exercise routines. It is predicted that these technologies will cut the costs of chronic disease treatment by as much as 50 % [18].

The application of digital intelligence on the consumer goods sector will increase the demand for employees with certain skills in software development and IT technologies [18]. However, the decentralisation of manufacturing might not lead to the creation of significant numbers of new jobs as greater automation will displace some of the often low skilled labourers [18, 19]. As such, greater education and training to adopt good analytical capabilities as well as software development capabilities would need to be a feasible option for many [21]. Thus a significant shift in the skill profile is required to deliver significant value [18].

Consumer goods companies such as Unilever,[2] Coca Cola[3] and L'Oreal[4] are already seeing the benefits that implementing digital intelligence can bring into their processes and business model. For example, these companies have established open innovation portals to outsource ideas for new innovations. Whilst the opportunities that digital intelligence can bring exist, the question still persists if meeting demand on a smaller scale, by at the same time delivering more regenerative and resilient systems of production and consumption, will be feasible for the consumer goods sector. To answer this question, it was necessary to define a series of criteria that

[2]https://oiportal.yet2.com/.

[3]http://us.coca-cola.com/happiness/.

[4]http://www.loreal.com/research-and-innovation.

define RdM and circular innovation in order to analyse case studies in this sector. This analysis aimed to have a better understanding of the feasibility of decentralising the consumer good sector whilst at the same time enabling circular innovation.

3 Criteria Definition and Case Study Analysis

The case study analysis used secondary data to examine 33 case studies of existing local, regional and global business models within the consumer goods sector. To choose the case studies they had to demonstrate: (1) the use of digital intelligence, (2) demonstrate de-centralised, re-distributed and circular production and consumption, and (3) had to be business to consumer in which the final user is an individual or household. The case studies analysed, referred to in Fig. 1, belong to different sub-sectors of the consumer goods industry according to Euromonitor International Database.[5] The sample of case studies was sourced from online resources such as reports, news, blogs' and websites, using key words such as 'distributed manufacturing', 'circular economy', 'personalisation', 'customisation', 'localisation', 'Internet of Things', 'Big Data' plus 'case studies' and 'examples.'

To analyse these case studies, different criteria were identified through the literature that could be used to define RdM and circular innovation. As both fields of research are still in their infancy, the available literature is disjointed, with multiple perspectives. The criteria were therefore developed based on the current review of literature and the most well used definitions of RdM and circular innovation, introduced in section one. Findings from the literature review were thematically analysed and categorised into themes and sub-themes by the researchers. This analysis resulted in five themes and 19 sub-themes to define RdM and four themes and 17 sub-themes to define circular innovation. These themes became the criteria against which to analyse each case study, case by case and are explained in detail in Sect. 3.1 through use of relevant literature.

3.1 RdM Criteria

The RdM criteria set was classified into *Localisation, Customisation, Distributed Ownership, Distributed Knowledge* and *Distributed Structure*.

(a) **Localisation**: RdM is about decentralising the raw materials and methods of fabrication, so the final product is manufactured very close to the final customer [22]. As such elements of localisation such as ***regional*** and ***urban*** settings needed to be considered. ***On-shoring***, where the repatriation of production from low cost locations is a continued trend, ***off-shoring*** in certain

[5] http://www.euromonitor.com/.

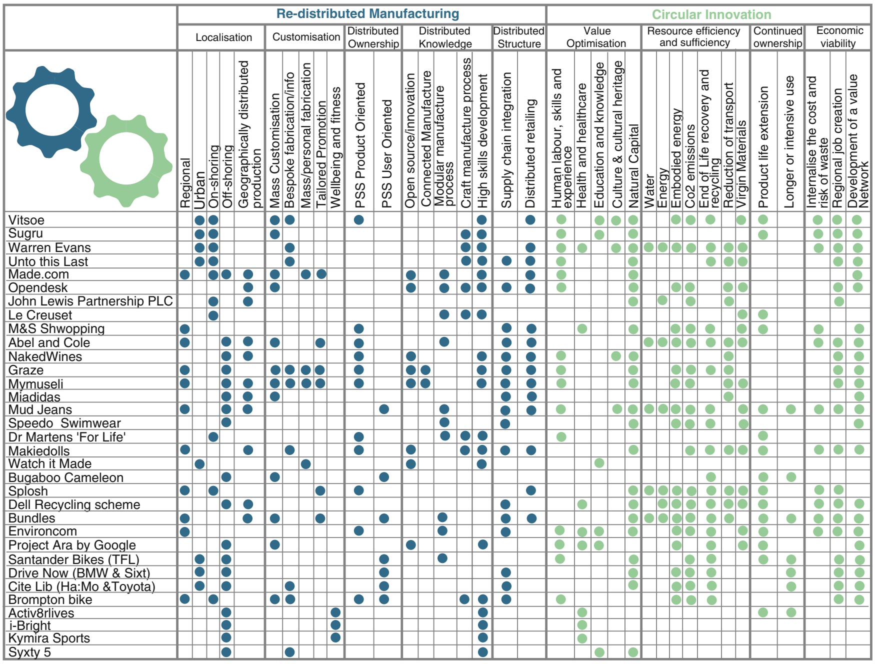

Fig. 1 Matrix: analysis of case studies in relation to RdM and circular innovation criteria

consumer goods sub-sectors will continue to happen in the short term due to proximity of raw materials and costs [14, 16]. Thus in the short term, we will see a ***geographically distributed production system*** in which will be based on a decentralised production structure with different facilities [12].

(b) **Customisation**: According to Kohtala [10] distributed production brings a range of emerging practices where households can affect what is produced from product personalisation to personal fabrication. In addition, she argues that with the use of digital intelligence, these practices had entered a mainstream of customisation in different forms. Thus, Kohtala [ibid.] classifies the distributed production landscape regarding the level of customisation and control over user versus its scale. This classification is: ***Mass customisation*** referring to individual mass production for a large market meeting different needs; ***bespoke fabrication and information***, which tailors individual products and services according to users needs; and ***mass/personal fabrication***, which uses open source design platforms to enable the democratisation of design. Customisation is also related to providing ***wellbeing***, ***fitness*** and ***tailored promotions*** [20].

(c) **Distributed Ownership**: The use of digital intelligence in distributed models of production and consumption are facilitating new business models in which ownership is shifting to access through providing robust products alongside long-term services [3, 14]. Distributed ownership has been studied by different scholars over the last 20 years under the topic of product service systems (PSS). A predominant scholar in this topic is Tukker [23] in which he classifies PSS into ***Product Oriented***, ***Use Oriented*** and Result Oriented. The latter is not considered as a category of distributed ownership as the production system is completely replaced by a service. E.g. BlablaCar[6] is a ride sharing platform in which drivers share their ride with other users heading to the same direction. In this case the production of 'new' cars are replaced by a service that uses existing cars.

(d) **Distributed Knowledge**: Distributed production needs the adoption of production networks, which are coordinated [24]. Thus distribution and transfer of knowledge will be essential to facilitate RdM [25]. Knowledge is seen in different forms. ***Open source innovation*** offers a closer interaction between consumer, designer and producer in which co-creation is busted through shared knowledge [10]. To take advantage of the opportunities that ***connected manufacturing*** could bring through the application of cyber-physical-systems known as ***Industry 4.0***, support and knowledge to ***develop the sufficient skills*** to be able to use demanding technologies would be essential [22]. ***Industry 4.0*** has the capacity to address the increasing complexity of products and their supply chain, by providing a full integration of information and knowledge between production and planning levels, and further to customers and suppliers [ibid.]. Distribution of knowledge can be finally referred to the use of ancient skills such as ***craft skills*** and bridging them with digital technologies. For example, Steffen and Gros [26] studied how decentralised production of furniture can benefit from transfer knowledge of ***craftsmanship production*** with digitalised production.

(e) **Distributed Structure**: Distributed structure refers to the structural changes needed to facilitate RdM. According to the Foresight Report [14] on the future of manufacturing, de-centralisation of manufacturing processes will need to have an effective use of global capabilities and adaptable logistic systems to achieve an ***integrated supply chain*** enabled by the use of digital intelligence. RdM might also disrupt current retail environments. This is continually increasing by shifting from physical retail to online retailing. Localisation and de-centralisation of manufacturing enabled by digital intelligence could enable manufacturers to become the retailer [14] allowing a ***distributed retailing*** process.

3.2 Circular Innovation Criteria

The circular innovation criteria were classified according to the 5 Principles of the circular economy [27], which were interpreted as *Value Optimisation* (Principle 2),

[6]https://www.blablacar.co.uk.

Resource Efficiency and Sufficiency (Principle 1 and 3)*, Continued Ownership* (Principle 4) and *Economic Viability* (Principle 5).

(a) **Value Optimisation**: According to Stahel [27] the main focus of the circular economy is to increase the optimization of value creation through an intelligent management of all resources including: ***human labour***, ***skills and experience***, ***health*** (including minimizing social issues) ***and healthcare***, ***education and knowledge***, ***culture and cultural heritage***, ***and natural capital*** (comprising biodiversity and natural resources).

(b) **Resource Efficiency and Sufficiency**: According to Stahel [28] efficiency and sufficiency are metrics to quantify material efficiency and reductions in material consumption and emissions. Efficiency and sufficiency should be achieved in: ***water***, ***energy***, ***embodied energy***, ***Co2e emissions***, ***end of life*** through recovery and recycling, ***reduction of transport*** and ***virgin materials***.

(c) **Continued Ownership**: Stahel [27] argues that continue ownership by selling goods as services or performance could internalise the cost of risk and of waste, and could provide future resource security. Moreno et al., [3] explored ***longer and intensive use*** (based on leasing and share use respectively) as circular models for continued ownership. In addition, Lacy and Rutqvist [9] identified ***product life extension*** as one of five circular business models based on continued ownership to recapture value of products through reuse, repair, remanufacture and remarketing goods.

(d) **Economic Viability**: A circular economy needs functioning markets [27]. Thus, economic viability is essential. To shift towards a circular economy that is economically viable, companies will need to think about ***internalising the cost of risk and waste*** [4], have an ***intelligent use of human labour*** and foster ***regional job creation*** [27], and ***developing a value network*** that is based on supply chain integration [4].

4 Findings

The case studies were analysed, case-by-case, against the criteria of RdM and circular innovation explained above. Through using secondary data each case study was assessed to understand if they met or not each criterion (Fig. 1) where a criterion was not found to be represented in a case study the field was left blank. The analysis was undertaken by the first author and arbitrated by the second. Once the analysis was complete a workshop was undertaken with a panel of three experts from across the fields of design, consumer goods and digital intelligence, to validate the criteria, selection of case studies and analysis. Figure 1 represents a matrix in which the case studies (vertical axis) were analysed against the RdM and circular innovation criteria (horizontal axis). A circle was used to depict what criteria was met by each case study.

4.1 Types of RdM

From this analysis, it became evident that there were several different types of RdM in which circular innovation characteristics were identified. Further analysis of the case studies was undertaken, particularly focusing on: the application of big data, the integration of distributed knowledge between the production and consumption processes, the levels of customisation that can be achieved, the potential to optimise and deliver value whilst at the same time enabling close-loop systems of production and consumption, and the scale of de-centralisation and localisation. From this analysis three types of RdM with circular innovation characteristics were identified (Fig. 2) explained below.

4.1.1 Distributed Production and Services

This model represents distributed manufacture that captures big data to monitor the processes of production and consumption. From the three models, this is the one that has the least potential of capturing and delivering value and is most closely linked to our current system, therefore the most cases were identified. This is because most of its capabilities relies on monitoring production and consumption processes. Also, it mainly happens off-shore with some on-shore capabilities of manufacture and re-manufacture as well as local capabilities to manage logistical operations. Big data is used to enable mass customisation as it flows just in one direction. Some closed loops of material flows could be captured through

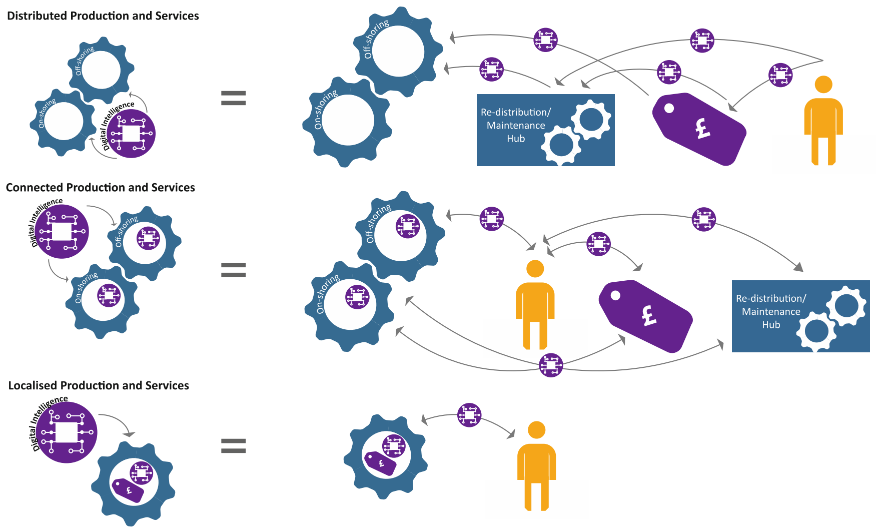

Fig. 2 Types of RdM models with circular innovation characteristics

monitoring end users. Case studies that were analysed as having these characteristics and represent this model, as depicted in Fig. 1, include Sugru, M&S Shwopping, Slosh and Environcom.

4.2 Connected Production and Services

This type represents a distributed and digitally connected model. This model can considerably capture high optimisation and delivery of value. This is because, despite manufacture still taking place off-shore and on-shore, it demonstrates a closer proximity to the end user that allows a radical model of consumer goods production, purchase and use. With the use of big data, users can engage in a data-driven open innovation process in which high level of customisation occur as demonstrated in the Opendesk case (Fig. 1). It also demonstrates high optimisation of manufacturing processes and logistical operations through the use of digital intelligence such as used by Abel and Cole (Fig. 1). In addition, the two-way flows of big data represented in this model allows material flows to be closed easily by the monitor, control and optimisation of resources.

4.2.1 Localised Production and Services

The third type identified represents a localised and highly digitally connected model of RdM where everything is done on-shore and the retail ecosystem is completely re-distributed contributing to the potential of capturing the highest value amongst the three models. This is because users are highly involved in an open be-spoke design and manufacture process, where consumer goods are produced and sold in the same physical or digital space. Personalisation is the key driver as well as shorter supply chains. This model enables high control and optimisation of resources as material flows happen in proximity to the factory and retail floor. The case study Unto this last is an example of this type of RdM (Fig. 1). This type of RdM was identified as being the least represented by the case studies as it is the most radical model requiring the biggest transformation to our current system.

5 Conclusions and Research Directions

RdM and circular economy are relative new concepts that can potentially disrupt current models of consumer goods production and consumption. This study carried out an integrative literature review of RdM and circular innovation definitions, fundamental drivers, and case studies to better understand the feasibility of decentralising the consumer good sector whilst at the same time enable circular systems. The study revealed that the integration of digital intelligence can enable a distribution of knowledge, structure, ownership and different levels of customisation, offering a more connected, meaningful and durable relationships with the end user. Digital intelligence can also can allow circular business models through automated monitoring, control and optimisation of resources and material flows. The study also revealed that the use of digital intelligence has incentivised the de-centralised, re-distributed and circular models of production and consumption. However, there is not an 'ideal' example of the potential that could be achieved by integrating RdM and Circularity into the business model, and that further value creation needs to be analysed. In addition, the opportunities and challenges of RdM and circular innovation are not still fully explored and questions still persist. For example, could a franchise manufacturing model work? What is the scalability going to look? What are the implications for intellectual property? What will be the consumer acceptance to these disruptive models? What will be the learning capabilities needed with the use of big data? How localised vs globalised models will be managed? And, do retail ecosystems will be competing with each other?

To answer these questions, the next steps of this research will focus on further analysing with primary and secondary data the value added of four case studies representing RdM and circular innovation. Three of these case studies will be based on a previously analysed case studies corresponding to one of the three types of RdM identified. The fourth will be a 'pilot case study' in which an ideal vision of RdM and circular innovation will be prototyped.

To conclude, it can be said that the potential for re-distributed manufacturing and digital intelligence to enable a regenerative economy is promising, but it is essential to understand where the value is captured and delivered to provide with the significant opportunities that the decentralisation of the consumer goods sector could bring.

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Makespaces: From Redistributed Manufacturing to a Circular Economy

Sharon Prendeville, Grit Hartung, Erica Purvis, Clare Brass and Ashley Hall

Abstract Redistributed manufacturing is an emerging concept which captures the anticipated reshoring and localisation of production from large scale mass manufacturing plants to smaller-scale localised, customisable production units, largely driven by new digital production technologies. Critically, community-based digital fabrication workshops, or makespaces, are anticipated to be one hothouse for this new era of localised production and as such are key to future sustainable design and manufacturing practices. In parallel, the concept of the circular economy conceptualises the move from a linear economy of take-make-waste to a closed loop system, through repair, remanufacturing, and recycling to ultimately extend the value of products and materials. Despite the clear interplay between redistributed manufacturing and circular economy, there is limited research exploring this relationship. In light of these interconnected developments, the aim of this paper is to explore the role of makespaces in contributing to a circular economy through redistributed manufacturing activities. This is achieved through six semi-structured interviews with thought leaders on these topics. The research findings identify barriers and opportunities to both circular economy and redistributed manufacturing, uncover overlaps between circular economy and redistributed manufacturing, and identify a range of future research directions that can support the coming together of these areas. The research contributes to a wider conversation on embedding circular practices within makespaces and their role in redistributed manufacturing.

Keywords Redistributed manufacturing · Circular economy · Design · Making

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1 Introduction

In its vision for manufacturing in 2030, the EU (2015) identifies megatrends of mass customisation, flexible, responsive, personalised and integrated (in homes) manufacturing, enabled by metropolitan manufacturing ecosystems which are built through the digitisation and virtualisation of society, as well as the diffusion of new production technologies. Such digitisation is an enabler for Redistributed Manufacturing (RDM), which sees a move away from centralised production facilities, towards local manufacturing and the use of digital technologies, leading to shortened supply chains and thereby reduced transportation impacts on the environment. In doing so, RDM is also expected to reduce waste (through digital production technologies) and energy consumption of production through shortened supply chains [21]. Critically, community-based digital fabrication workshops, or makespaces, are anticipated to be one hothouse for this new era of localised production and as such are critical to future sustainable design and manufacturing practices.

In parallel, the concept of the circular economy (CE) conceptualises the move from a linear economy of take-make-waste to a closed loop system [7] through repair, remanufacturing, refurbishment and recycling, to maintain materials and resources in a closed cycle. Its integration in international policies from China, through its 11th and 12th ‘Five Year Plans’ [17], to Europe through its Circular Economy Roadmap [6] reflect the increasing importance of CE globally. Despite the potential interplay between RDM and CE, there is limited research exploring this relationship. In light of these interconnected developments, the aim of this paper is to explore the role of makespaces in contributing to the CE through RDM activities.

2 Literature Review

2.1 The Emergence of Makespaces

Community-based digital fabrication workshops, or makespaces, are organisationally diverse (Hielscher and Smith 2014), creative and social places where makers can network, learn and access a variety of (previously inaccessible) fabrication tools and technologies. Despite limited research on the characteristics and activities of makespaces in general, some studies exist (Hielscher and Smith 2014). Understanding the activities and structures of makespaces is important, given the range of activities underway, disparate governance structures, scope of ambitions, and diversity of local contexts (Hielscher and Smith 2010). Troxler [19] devised a framework to interpret the diversity of makespaces, from tech shops, to sharing platforms, Fab Labs, and hackerspaces spanning activities from open hardware design to repair workshops. Indeed, some say that, through the act of making itself, the new ‘prosumer’ can foster a stronger connection with the object being made (Kohtala and Hyysalo 2015) and therefore a longer product life can be expected.

Nonetheless, at the heart of many maker communities are values that relate to sustainability. ‘A third place’, Kohtala [12] identifies the tendency to collaborate openly, to adopt industrial ecology principles, to focus on local problems, and to draw on needs-based solutions. Makespaces are defined by local values, openness and freeness, [10]; collaboration and sharing [20]; respect for resources and cultural assets [12]. However, Kohtala [12] also states that socio-economic imperatives (short-term survival) mean environmental issues are not given much concern.

2.2 *Re-distributed Manufacturing (RDM)*

While there are common threads, a clear consensus on what RDM actually entails and its benefits have yet to be determined. The EPSRC [8] identifies: local manufacturing for local communities and economies; cloud manufacturing services; dynamic production environments capable of creating customisable or multi-variant products; sustainable/resource efficiency; and flexibility/agility in production suited to short ramp-up times as key characteristics of RDM. Table 1 presents a list of definitions of RDM reflecting these characteristics and more.

One catalyst for the increase in makespaces globally, is the diffusion of digital production technologies such as additive manufacturing; however subtractive processes (5-axis CNC) and other processes like laser cutting are also important. These new technologies are purported to contribute to both increasing and reducing emissions and energy usage. For example, Gebler et al. [9] claim, with somewhat large deviations, that 3D-printing has the potential to reduce costs (for companies) by 170–593 billion dollars (US), the total primary energy supply by 2.54–9.30 EJ and CO_2 emissions by 130.5–525.5 Mt by 2025.

Table 1 Defining redistributed manufacturing

Source	Definition
WEF	…enable…efficient use of resources, with less wasted capacity in centralized factories…to reduce the overall environmental impact of manufacturing: digital info is shipped over the web rather than physical…and raw materials are sourced locally…reducing the energy…for transportation
BIS	…potentially disruptive impact on supply chains. The development of AM [additive manufacturing] faces unique technical challenges, but there are huge potential benefits including the possibility for more localised manufacturing and the reduced need for part inventory
EPSRC	Technologies, systems and strategies that change the economics and organisation of manufacturing, particularly with regard to location
Kuhnle (2010)	A decentralised approach could make production systems more flexible and adaptable

However, the risks of digital fabrication are also recognised. Smith and Hielscher (2015) see diminished scale leading to process inefficiencies and disruptions in waste collection as key issues. Drizo and Pegna [4] raise the issue of toxicity of rapid-prototyping materials and highlight the broad lack of knowledge on the life cycle impacts of related materials. In addition, the trade-offs between energy consumption, the crossover point at which additive technologies become less energy intensive, given the production volumes, needs to be fully understood. While the promise and vision for RDM within makespaces is compelling, there is limited understanding about what is being made. Some of the more 'needs-based' solutions Kohtala [12] alludes to are mentioned in the literature, such as a device which can monitor milk quality for farmers or skin conditions in rural areas [19]. In contrast, Gebler et al. [9] summarise key markets for the uptake of 3D-printing to 2025 including: consumer products, aerospace, automotive, medical components and tooling. Importantly, this illustrates a divergence from the activities of makespaces in general, from the sectors and goods forecasted to take up the opportunities. It also indicates the another potential significant trend of large-scale manufactures seizing the market opportunity, to localise their own production either through owned outlets or franchised operations.

2.3 Circularity: Circular Product Design and Circular Business Models

The terms circular product design and circular business models are derived from the overarching concept of the CE and are increasingly brought together through models and frameworks (Costa et al. 2014) [16]. In simple terms, a business model is about the way you do business [14] and therefore a circular business model can be viewed as a business model with a CE vision. Circular product design, promoted by Bakker et al. [1] is achieved through designing for attachment and trust; durability; standardisation and compatibility; ease of maintenance and repair; adaptability and upgradability. This is because, to realise a CE, changes in both product design practices and business models are critical [1, 18]. For example, Teece [18], states that product development needs to iteratively inform developments in the business model. Therefore, building linkages between design strategies and business models is important.

2.4 Literature Summary: Research and Practice Gap

The suggested benefits of additive technologies seem out of alignment with the observed characteristics of makespaces. For example, forecasts for market uptake of key technologies are linked to heavily regulated business-to-business sectors, whereas, the benefits observed (from the viewpoint of the makespaces) are around local solutions. Existing knowledge sees makespaces as powerful local connectors, with positive social impacts and the potential to build resilient local activities.

In addition, little research has been undertaken that demonstrates how waste can be reduced using digital production technologies and many questions remain about the environmental impacts of many of the materials and production systems used for digital fabrication. In addition, Troxler [19] states that most successful open hardware initiatives operate within market conditions and are not 'radically decentralized'. Another concern that appears to be overlooked in the literature, is how the on-demand nature, of a redistributed future, impacts on consumption levels in society, given the absence of any real basis to show that prosumption in and of itself, can overcome this. For example having on-demand local production may even lead to more irresponsible production and ever greater consumption.

3 Methodology

The aim of the research is to explore the interplay between makespaces, RDM and CE. In light of this the research question driving the research asks, 'what is the role of makespaces in a sustainable RDM future?' The research methods are qualitative and based on six interviews designed to explore this topic. The interviews were semi-structured, conducted online, recorded and transcribed. The interviewees were provided with a participant information sheet in advance of the interview to describe the purpose and format. The interviewees were selected from an initial list of 36 identified potential interviewees, based on their expertise on the topic, experience of setting up and running makespaces and to cover a wide range of geographical contexts. Table 2 presents an overview of the interviews and Table 3 describes the semi-structured interview questions. Finally, the interviews were analysed thematically, within and across cases.

Table 2 Overview of expert interviews

	Interviewee role	Date	Interviewee's location
1	Academic	14.08.2015	Finland
2	Makespace founder	5.08.2015	UK
3	Makespace founder/academic	22.06.2015	China
4	Makespace founder/academic	01.09.2015	UK
5	Makespace founder/academic	01.09.2015	Italy
6	Makespace founder/researcher	31.07.2015	Spain/Venezuela

Table 3 Semi-structured interview guide

	Questions
1	Are you aware of the concept of redistributed manufacturing (RDM)? What do you understand RDM to mean? Can you cite any examples?
2	What do you think the importance of RDM is in terms of circularity?
3	From your perspective, do you think Makespaces have a role in a RDM future?
4	What do you think RDM mean in terms of circularity? [a] What does this mean for the future of manufacturing?
5	What do you think this idea of circularity means in the context of Makespaces?
6	What examples of circularity have you seen (in Makespaces), if any?
7	What do makespaces/the people of the MS need to develop/improve circular practice (rationale for development of activities/tools)?
8	What is the role of technology in makespaces? What do these technologies mean in terms of circularity? What are the (1) barriers (2) enablers (3) opportunities?
9	What is the role of people in makespaces? What do these people mean in terms of circularity? What are the (1) barriers (2) enablers (3) opportunities?
10	What other characteristics would you say encourage a circular makespace?

4 Results and Analysis

This section presents the results of the interviews with an integrated thematic analysis.

4.1 Redistributed Manufacturing: Terminology and Examples

The concept of RDM was not familiar to all of the interviewees and during the interviews the term 'distributed manufacturing' was raised as a more familiar phrase. Nonetheless, the research identified that RDM is characterised by the following aspects:

- Open source, open design, sharing practice, knowledge and skills (as well as products).
- Reshoring manufacturing to Europe.
- Open, digital networks.
- Collaborative and open innovation.
- Enabled by diffusion of new technologies.
- Personalisation and customisation.
- Prosumption: bringing the custodian closer to manufacturing processes.
- People-focused: not solely technology-centred/driven, but also about local networks and social interactions.

However, one interviewee stated that RDM is really a 'partial phenomenon', widely discussed over the last ten years but with very few examples in practice. Those examples that were cited, illustrate more meso-level (urban activities such as agriculture and distributed energy projects) rather than directly relevant to the production of manufactured products.

The respondents communicated that makespaces activities are predominantly the prototyping and testing of ideas and therefore are promising spaces for incubation and experimentation of new potential circular solutions and ideas. While local production is a goal, it's not happening at any significant scale. Current outputs identified include components or prototypes that go on to be manufactured in a 'traditional' manufacturing environment. 'The maker movement talks so much about local production, but in reality that doesn't happen'. Despite this, interviewees who play a more active role within makespaces responded favourably to the future prospects for batch production perceiving an increase in demand on the horizon. Examples cited as being close to, or moving towards RDM, and CE, but not wholly RDM in the sense that some characteristics of the approach is centralised, include:

- Fairphone, through its community-focus, ethical suppliers and material use.
- Urban agriculture which is well developed at a city level e.g. Farm Shop Dalston.
- Off-grid distributed energy solutions—energy is generated or stored by a variety of small, grid-connected devices referred to as distributed energy resources (DER) or distributed energy resource systems.
- Will.i.a.m collaboration with Coca Cola to produce 'Ekocycle' which can process recycled PET (Coca Cola) bottles.
- Filabot—sustainable 3D printing, recycling parts to make new filaments which both saves money and reduces waste.
- Solowheel, rapid versions developed, already in its 3rd generation after 6 months, in the loosely coupled manufacturing ecosystem of Shenzhen, China.
- Dexta Robotics' Dexmo by Seeed Studios, the Shenzhen-based firm was founded as a bridge between Western makers and China's agile manufacturing ecosystem; aiming to design with manufacturing specs in mind; its Open Parts Library (OPL) catalogues compatible components for the most widely used parts in printed circuit board (PCB) designs.

4.2 The Role of Makespaces in a Sustainable Redistributed Future

From the interviews it is clear that makespaces are perceived to play a key role in an RDM future. This is perceived in a number of ways and some of these perspectives are reflected in the wider academic literature:

- Through the implementation of shorter production loops to reduce waste and environmental impacts of transport.
- Additive technologies can facilitate repairability of products, by on-demand manufacturing of spare parts to extend the life of products. While this is broadly beneficial for society, in some cases (e.g. electronics) repairing products may not be the best option, if more energy efficient solutions have come on to the market.
- Makespaces can encourage a broader demographic of people to engage in making. Assuming that people care more about things that they have had a role in making, thereby increasing the 'responsibility' of individuals and their attachment to products. Nonetheless, some interviewees communicated scepticism about the realities of this at present, but also indicated that with the right support mechanisms (governmental incentives) this could be a future reality.
- Open design practices, underpinned by sharing design files and solutions through digital networks, can address barriers to wider diffusion of CE. For example through the development of meaningful/viable open source (legal/business) framework, to overcome intellectual property issues that currently hinder CE, but also by fostering greater supply chain transparency.

Nonetheless, broadly speaking, within makespaces, the understanding of the concept of CE, and indeed wider sustainability, varies greatly. This is clear when comparing the activities of, as one cited example, Amersfoort Lab, which takes a deeply embedded sustainability approach (akin to industrial ecology) in comparison with other spaces that fail even to implement basic waste separation facilities. Other visionary industrial ecology-like examples were cited, such as the ability to grow, harvest and process resources in localities close to makespaces. This example also touches on the widespread perspective that the greatest potential for makespaces is seen in opportunities for incubation of creative start-ups, experimentation with new ideas and the space to test different approaches and innovative solutions. This relates to the capacity of makespaces to effectively educate, build and share skills and knowledge, which was consistently and enthusiastically communicated during the research.

4.3 Challenges and Opportunities

Certain conditions limit the capacity for makespaces to implement RDM and CE principles. Similarly, many opportunities exist. Tables 4 and 5 summarise these findings. It is important to note that many of the challenges identified are not unique to makespaces as organisational entities, but rather reflect a wider body of knowledge on barriers to sustainability in industry and this literature should and can be drawn on to inform future interventions [15] (Prendeville et al. 2010).

Table 4 Challenges to redistributed manufacturing and circular economy from the viewpoint of makespaces

Challenges to RDM	Challenges to CE
Scalability • Uncertain how to mature from prototyping to batch production • Supply chain management issues e.g. space (storage facilities) • Need to develop knowledge of production management • Need to identify and develop means to access local markets *Context* • Need for routes to local integration and methods to access and manage local material supplies *Collaborations and competition* • Greater need for collaborations with producers • Competition with large scale producers who seek to downscale and localise production facilities *Skills and education* • Educational tools and guidance for makers to become CE-ready • Educational tools and guidance to encourage local actors to engage with local production	*Know-how* (*lack of*) • Sustainable design • Supply chain transparency • Efficiency (product and machining) *Leadership* • Lack of aware 'eco-champions' to drive initiatives • Knowledge-action gap *Organisational challenges* • Time poverty, money, personnel • Decisions on materials and equipment, can be guided by bureaucracy and the need to streamline processes • Mission drift *Networks and resources* • Lack of a central, connected, space to access relevant knowledge and support • Invisibility and intangibility of issues • Dated/inefficient technologies that are far from state-of-the-art • Lack of incentives (market demand and/or governmental) for makers to develop sustainable/regenerative goods and services *Markets* • Perceived lack of market demand for sustainable goods

4.4 Overlaps Between Makespaces, CE and RDM

Figure 1 summarises some of the key findings of the research, showing the current state of interplay between makespaces, CE and RDM. This figure is derived from the existing definitions of RDM and CE combined with the insights from the interviews. For example, it conveys the current role that makespaces play in CE, by contributing to repair. In addition, it shows how the strong social dimension seen within makespaces, could enrich CE to move towards a deeper sustainability approach that unifies social and environmental imperatives. This figure captures a picture of the research at a point in time, but will be adapted and built into a theoretical framework for future research.

Table 5 Opportunities for redistributed manufacturing and circular economy from the viewpoint of makespaces

Culture • Underlying ethos of openness and collaboration, which can be built on to diffuse and share best-practices, for example: – Use of digital networks and sharing platforms provide an existing infrastructure through which to share knowledge, therefore, disseminating relatively simple technical knowledge on (for example) cutting practices to reduce waste, existence of local industrial symbiosis programmes and efficient ways of running machines is likely to have a strong positive effect • Experimentation is facilitated and encouraged • Natural investment in practical skills development and education and learning
Specialist expertise and capacity building • Skills and knowledge for product repair and reverse-engineering of products through product tear-downs is common practice • Building capacity to design and make localised product solutions that are more effective in their context than ubiquitous global mass product offerings • Customisation for local consumers • Responding to changing contexts, rapidly changing climate challenges
Unifying social and environmental sustainability • Potential to unify social and environmental sustainability practices • Evidence of industrial-ecology like approaches in combination with strong social, local networks
Innovation, and incubation • Potential to build in circular practices at the early stages of product conceptualisation and development • As paces for incubation and experimentation of new potential circular solutions and ideas

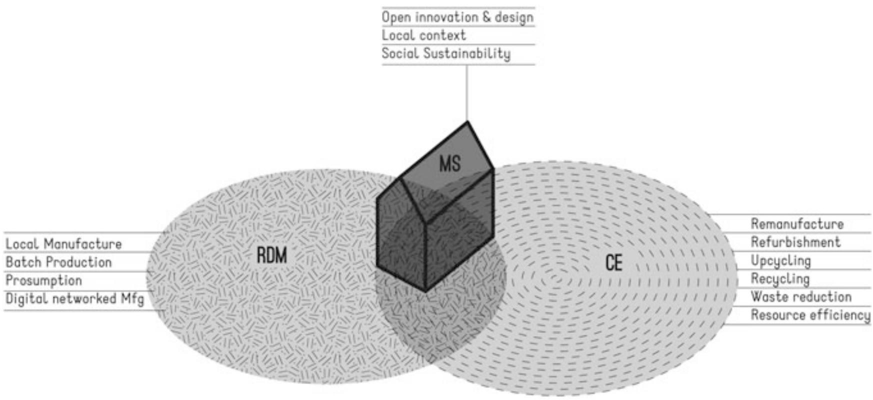

Fig. 1 Conceptualising overlaps between CE, RDM and MS

5 Conclusion

This paper set out to discuss the role of makespaces in contributing to the CE through RDM by identifying key challenges to overcome. We found that these challenges many and varied (described in Table 4) and illustrate the need for a broad set of actions from funding bodies, local and national government to support the professionalisation of makespaces to effectively play a role within a sustainable RDM ecosystem. In addition, the research uncovers a clear set of positive opportunities which can be harnessed by makespaces to increase their capacity to survive and bridge the gap to the CE (Table 5).

The literature review, combined with the interview data has provided an initial conceptual description of the overlap between makespaces, RDM and CE (Fig. 1). This is a starting point to underpin future research on this topic.

From the analysis and literature review, we forecast a rapid divergence of makespaces in the mid-term and this should be considered within any future support actions from governmental and funding agencies. This segmentation of makespaces is important, because, the research highlights that there is a risk of undermining the current value of makespaces, many of which foster social cohesion in their local contexts. Others, based on their mission, capacities and capabilities are potentially more suited to organised RDM activities. This combination of attributes means makespaces are in a unique position to unify social and environmental sustainability imperatives.

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An Exploratory Study of the Resilience of Manufacturing in the Cardiff Capital Region

Anthony Soroka, Mohamed Naim, Gillian Bristow and Laura Purvis

Abstract Sustainability in all its guises is important for the long term continuance of manufacturing. The ideas of local sustainability and resilience have become increasing popular topics for study. The drive for economic resilience is causing governments to look at regional strategies to improve economic sustainability and resilience. A recent example of this is the establishment of a Cardiff Capital Region (CCR) in Wales. This exploratory study takes an initial look at the resilience of manufacturing in the CCR vis-à-vis economic resilience using the FAME dataset and QuiScore measure. Results indicate that on the whole manufacturing looks broadly healthy. However, some potential areas of concern were identified, many of the biggest and healthiest companies are not headquartered in the CCR, whereas 98 % of the weakest companies are, and there are inter and intra sectorial differences. The study also suggests that measures such as QuiScore should perhaps not be used in isolation as its methodology is unknown and a large number of companies do not have QuiScores.

Keywords Sustainability · Resilience · QuiScore · Manufacturing

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1 Introduction

Shaw and Newby [1] in their exploration of local economic development define sustainability as “the capacity for continuance more or less indefinitely into the future”. As such it incorporates the many facets of sustainability, economic, environmental, and social etc. Many definitions exist, Bonevac [2] states that there are over 300 definitions in literature, going as far as to say that “Devising criteria and measures of sustainability has become a cottage industry”.

In order to be sustainable the manufacturing sector also needs to have resilience: “the ability of a system to return to its original state or move to a new, more desirable state after being disturbed” [3]. Specifically a firm’s vulnerability/capacity to survive and adapt, resist decline and respond to opportunities [4]. Allied to this is the concept of regional resilience which has emerged as a trend that is developing a widespread appeal, in particular when examining how regions have fared during the recent economic crisis [5].

Government are paying increased attention to regions, in autumn 2011, the Welsh Government’s Minister for Business, Enterprise, Technology established a Task and Finish Group to consider the evidence for city regions as economic drivers, and to identify potential city regions in Wales. As a result of this in November 2013 Cardiff Capital Region (CCR) Board was established, with confirmation of £580 million of funding announced by the Welsh Government in November 2015. The CCR incorporates the following authorities: Blaenau Gwent; Bridgend; Caerphilly; Cardiff; Merthyr Tydfil; Monmouthshire; Newport; Rhondda Cynon Taff; Torfaen; and The Vale of Glamorgan. The CCR has a total population of c.1.5 million (c. 50 % of the total population of Wales) and generates >50 % of Wales’ Gross Value Added (GVA), as such it plays a key part in the economy of Wales.

This exploratory study aims to examine the manufacturing resilience of the CCR using the proprietary QuiScore provided within the FAME database (which contains financial and other data of c.4 million UK registered companies). Investigating any potential impact this could have on the resilience of manufacturing within CCR. The paper is structured as follows: a description of the QuiScore together with examples of its application is provided, followed by an investigation of the manufacturing sector in the CCR, a more detailed investigation of several sectors, and finally the conclusions.

2 QuiScore

2.1 QuiScore Description

The QuiScore was originally developed by Qui Credit Assessment Ltd [6] and now provided by CRIF Decision Solutions [7] is a measure of the likelihood of a particular company failing within the 12 months period following the date of calculation. According to Bureau van Dijk the publishers of the FAME database, the QuiScore is calculated using statistical and modelling techniques to select and apply a weight to data elements (variables and coefficients) that are most predictive of business failure [8].

As already noted this is a proprietary method and as such no details have been disclosed of the algorithm and the data it uses. However, in information provided to subscribers to the FAME database, Bureau van Dijk explain that the data used to generate QuiScores are extracted from the following areas of company information:

- Account information
  - Profitability
  - Solvency
  - Leverage
  - Business structure
  - Capitalisation
  - Working capital
  - Cash flow
  - Liquidity
  - Productivity
  - Trend
- Director history
- Registry Trust Information: County Court Judgements (CCJs)
- Shareholder funds
- Lateness in filing accounts

All this information is included during the process that evaluates the QuiScore, taking into consideration the medium-term life cycle of the company as a whole. With the selection of variables and application of weightings to them claimed to be the result of extensive data analysis. The development of calculation models considers a combination of the "good" and "bad" performance of businesses held in the source database.

According to Bureau van Dijk the QuiScore, is provided within the database as a number within the range 0–100, with 0 representing those companies with the highest likelihood of failure. As shown in Table 1 the scores have been divided into five distinct bands.

Bureau van Dijk expands upon this information by providing the percentage of likelihood of failure based on the QuiScore range as shown in Table 2.

2.2 *QuiScore in Research*

Within academic research literature the QuiScore is used in a variety of ways, a common application is to the assessment of the strength of individual companies,

Table 1 QuiScore bands. *Source* Bureau van Dijk

Qui band	Description
81–100 secure	Companies in this band tend to be large and successful public companies. Failure is very unusual and normally occurs only as a result of exceptional changes within the company or its market
61–80 stable	Company failure is a rare occurrence and will only come about if there are major company or marketplace changes
41–60 normal	This band contains many companies that do not fail, but some that do
21–40 unstable	As the name suggests, there is a significant risk of company failure; in fact, companies in this band are, on average, four times more likely to fail than those in the Normal Band
00–20 high risk	Companies in the High Risk sector may have difficulties in continuing trading unless significant remedial action is undertaken, there is support from a parent company, or special circumstances apply. A low score does not mean that failure is inevitable

Table 2 QuiScore likelihood of failure. *Source* Bureau van Dijk

QuiScore range	Percentage likelihood of failure (%)
00–10	100.00
11–20	50.00
21–30	29.00
31–40	11.00
41–50	6.00
51–60	1.00
61–100	0.00

such as rating of credit risks [9], or assessing the strength of companies [7]. These are the sorts of applications that one would expect to see from a credit risk measure.

Some studies have used QuiScores to examine other factors for either individual companies or groups of companies. Examples of this include examining whether there is an association between the number of risk disclosures by companies and a variety of risk measures [10], how a firms' level of global engagement is reflected in their financial health [11], the impact of private equity on innovation activities, and the links between financial health and exporting [12]. This use of the QuiScore to examine both individual companies as well as groupings suggests that its use in examining manufacturing in the CCR is an appropriate technique (at the exploratory stage at least). This conclusion is further strengthened by it being used in the identification, for further evaluation, of companies in the forging sector within the West Midlands area in the UK [13].

Of note is that the proprietary nature of the QuiScore has been noticed which has encouraged research that is aimed at replicating the QuiScore method [14].

3 Analysis of Economic Resilience of CCR

The FAME dataset was interrogated in September 2015 using the search criteria shown in Table 3. This resulted in 2607 companies being identified, once all companies without a current QuiScore and a non-manufacturing primary SIC (UK Standard Industrial Classification) were eliminated this was reduced down to 1796. Two points of note are that the SIC is self-declared by the company and that the large number of companies without a QuiScore suggests that it uses information some smaller enterprises may not be obliged under UK tax law to provide.

3.1 Overall Manufacturing Resilience

In order to the investigate the overall economic strength of the CCR the QuiScores need to be examined. The study examines, all companies, the top and bottom companies (by turnover figure provided in FAME), and the companies with no turnover (those which by law are not required to report one).

The figures shown in Table 4 are positive in that average (mean) QuiScores are all in the Normal or better band. However, a slightly different picture is painted when the data is examined in more detail, especially for those companies in the Bottom 50 or those without turnover. The standard deviations are sufficiently large that a significant proportion of them will fall into unstable band. In total 18 of the Bottom 50 companies are Unstable or High Risk, and for the 1357 companies with no recorded turnover 494 are Unstable or High Risk (36 %).

Additionally the mean for the Top 50 companies is slightly lower than that for the Top 100 or 250 companies, the cause appears to be that one of the companies had a very low QuiScore (24) which had an impact on the mean.

More in-depth analysis of this data was conducted where average turnover, mean and median numbers of trading addresses were examined. Upon analysis of the data it was noticed that there was one outlier company with several hundred trading address (which manufactured in the CCR), this company was therefore excluded. This data is shown in Table 5.

One thing that becomes apparent from looking at Table 5 is that there is strong evidence suggesting that the top companies in CCR (in terms of turnover) are national or multi-national primarily due to the number of trading addresses a company might have. The mean number of addresses is over 23 for the Top 50

Table 3 FAME search criteria

Criteria	Value
Company status	All active companies
Location	CCR region—CF & NP postal regions (all trading addresses)
Industry	10,000–32,990 UK SIC (2007)

Table 4 Average QuiScores for CCR manufacturing

	Average type	Value	Qui risk
All	Mean (σ)	53.50 (25.24)	Normal
	Mode	50.00	Normal
	Median	50.00	Normal
Top 50	Mean (σ)	86.06 (12.40)	Secure
	Mode	94.00	Secure
	Median	90.00	Secure
Top 100	Mean (σ)	87.74 (10.55)	Secure
	Mode	90.00	Secure
	Median	91.00	Secure
Top 250	Mean (σ)	88.07 (12.19)	Secure
	Mode	94.00	Secure
	Median	92.00	Secure
Bottom 100	Mean (σ)	62.20 (25.54)	Stable
	Mode	90.00	Secure
	Median	67.00	Stable
Bottom 50	Mean (σ)	48.47 (24.93)	Normal
	Mode	16.00	High risk
	Median	48.00	Normal
No Turnover	Mean (σ)	44.29 (19.30)	Normal
	Mode	50.00	Normal
	Median	46.00	Normal

Table 5 Average QuiScore, turnover and trading addresses

	Qui risk	Average turnover (£000's)	Mean trading addresses	Median trading addresses
All	Normal	165,535	2.78	1.00
Top 50	Secure	1,215,706	23.14	16.00
Top 100	Secure	663,629	19.11	5.50
Top 250	Secure	285,761	12.30	2.00
Bottom 100 (with turnover)	Stable	1863	1.22	1.00
Bottom 50 (with turnover)	Normal	280	1.10	1.00
No turnover	Normal	N/A	1.19	1.00

companies, as already noted in this study this average can be skewed by having several companies with a large number of locations. Examination of the Median gives a value of 16, which confirms that a significant proportion of these companies have more than one or two trading addresses. These multi-address companies fall into two broad categories manufacturers that also retail and large industrial corporations.

Whilst the overall QuiScore is high and these top companies are considered to be secure, which is positive, the number of trading locations could be cause for concern. Especially if the registered office isn't in the region and/or the company is a multinational. Also a trend within supply chain management is that of re-shoring, so such a company might be tempted to have manufacturing closer to the head office. Referring back to the FAME data for the Top 50 companies in the CCR it was discovered that only 9 of the 50 have their registered office in the CCR (3 of which in the same group of companies). When FAME data is examined for companies with a QuiScore ≤10, only 2 of 108 have their HQ outside the CCR. This suggests that weaker companies may have stronger links to the communities they are based in, which could be both positive and negative from the perspective of sustainability and resilience of a particular community.

3.2 *Sectorial Resilience*

The average, minimum and maximum QuiScore, and standard deviation of the average to $\mp\sigma$ for each manufacturing sector based on the UK SIC (Standard Industrial Classification) codes are shown in Fig. 1.

Broadly speaking the sectors look similar. However, there are two sectors that are particularly interesting. Firstly Chemicals, it has highest average QuiScore($\bar{x}$) 68.3, highest $\bar{x} - \sigma$ and highest $\bar{x} + \sigma$—so much so that all within range are above 40 and hence are in the Normal band or better. Secondly Wearing apparel, it has lowest average QuiScore ($\bar{x}$) 32.1, the lowest $\bar{x} - \sigma$ and lowest $\bar{x} + \sigma$. The following section examines these two sectors in more detail.

3.2.1 Chemicals Sector

The average QuiScores of the sub-sectors are shown in Table 6, as can be seen they generally fall into the Stable or Secure bands. The only sub-sector that doesn't is the manufacture of soaps and detergents, although it is still in the Normal band. This sub-sector has a large discrepancy between companies: seven of the twelve companies have a QuiScore below 40, whilst the remainder have a score over 50.

Further examination of data from FAME for the sector shows that the companies with the highest QuiScore have their registered offices both inside and outside of the CCR. However, those with the lowest QuiScore are registered in the CCR. Additionally many these companies have had poor QuiScores for several years. This does raise a question about whether they might be trapped in a vicious cycle where because of the low QuiScore tier 1 or 2 suppliers may not be willing to use them.

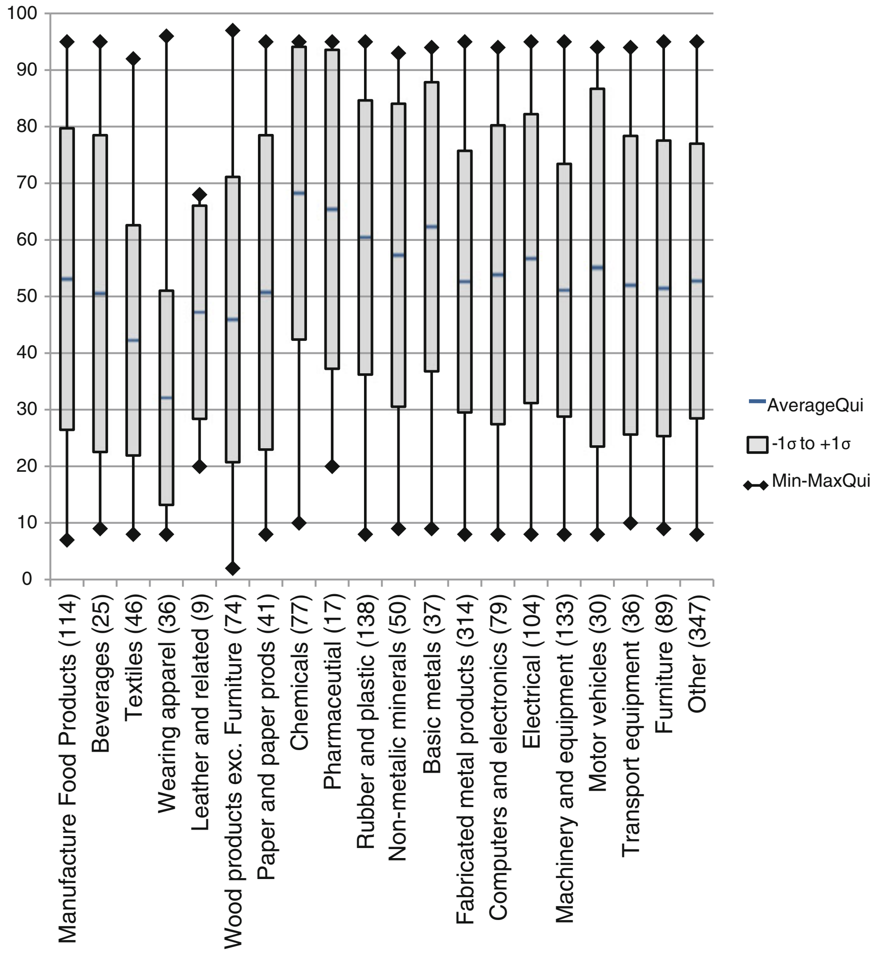

Fig. 1 QuiScore of industrial sectors (number of companies in sector) in CCR

Table 6 Chemicals sub-sectors

Sub-sector	Average QuiScore
201. Manufacture of basic chemicals, fertilisers and nitrogen compounds, plastics and synthetic rubber in primary forms	75.43
202. Manufacture of pesticides and other agrochemical products	61.00
203. Manufacture of paints, varnishes and similar coatings, printing ink and mastics	70.80
204. Manufacture of soap and detergents, cleaning and polishing preparations, perfumes and toilet preparations	48.67
205. Manufacture of other chemical products	68.33

Table 7 Wearing Apparel sub-sector

Sub-sector	AverageQui
141. Manufacture of wearing apparel, except fur apparel	32.46
143. Manufacture of knitted and crocheted apparel	20

3.2.2 Wearing Apparel

The average QuiScores of the sub-sectors are shown below in Table 7, both of the sub-sectors fail to fall into the Normal band.

Further examination of data from FAME for the sector shows that the company with the highest QuiScore (and the only company within the Secure band) has their registered offices outside of the CCR. However, those with the lowest QuiScore are registered in the CCR. Despite this these low QuiScores there are several example of companies trading for at least ten years with QuiScores in the 15–25 (High Risk—Unstable) range. This is something that is very different to the Chemical sector where no companies have been able to sustain such poor scores for ten years or more. This suggests that something else might be occurring that helps keep these companies afloat—perhaps a sectorial or regional resilience aided by social networks or lower regulation/overheads.

4 Conclusions

Companies based in multiple locations, in particular those whose registered offices are not located in the CCR, may have little attachment to a particular area. This could be negative with regards to resilience and long term sustainability in a region.

There also appears to be a trend that the companies with the lowest QuiScore are based within the CCR. Whereas companies with high score are often based outside of the CCR.

The work has also identified that there are companies, whose poor QuiScores suggest that they should not be in business yet have managed to sustain themselves for extended periods of time. This suggests that there may be other factors involved that this study has not been able to identify. Additionally it raises potential questions about the QuiScore and how it might compare to other potential resilience measures such as Altman's Z-score [15]. Also there appears to be a sectorial difference in the ability of companies to sustain themselves whilst having poor QuiScores.

5 Limitations and Further Work

A limitation of this work is that it only uses the QuiScore, whose method is unknown and as such a large number of companies are excluded from examination. Further studies could potentially benefit from using alternative measures of company wellbeing. Also this work does not examine all of the industrial sub-sectors, also it doesn't examine the historical data of those companies that have been dissolved. Finally due to limitations of the dataset it doesn't look at the interactions between companies, and their supply chains.

As a result of this exploratory study it evident that there a large number of potential factors that will require further investigation. As a result of this future work will need to address the following issues and questions:

– Mapping of sector v QuiScore v region
– Use of alternative measures of company strength (such as Altman's Z-score)
– More analysis of sectors, type of company, registered address locations and QuiScores, and the subsequent regional implications
– Longitudinal studies based on historic company data
– Identification of the factors contributing to some sectors being able to sustain poor QuiScores for longer
– Examination of resilience from the regional and sectorial perspectives
– Examination of dissolved companies within the region

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Design of an Integrated Assessment of Re-distributed Manufacturing for the Sustainable, Resilient City

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Abstract Re-distributed manufacturing (RDM) has the potential to be beneficial to business and society through creating jobs, reducing the environmental impacts of production, and improving organizational and societal resilience to future disturbances. The potential impacts of RDM for a city-region are complex and their exploration requires the consideration of a wide range of issues—societal, technical, logistical, and environmental. This paper discusses the use of an approach called Integrated Assessment to carry out an initial scoping of the issues. A research framework for RDM, and the key themes from a workshop that explored the causal relationships between different types of resilience, sustainability, and the manufacturing sectors are presented.

Keywords Systems thinking · Sustainable manufacturing and society · Re-distributed manufacturing · Manufacturing resilience

1 Introduction

The research project *Redistributed Manufacturing for a Resilient, Sustainable City* (RDM|RSC) is studying the impact of moves towards smaller-scale and local manufacturing with a focus on the resilience and sustainability of a city—Bristol, UK—and its region. One definition of Re-distributed Manufacturing (RDM) is: '*Technology, systems and strategies that change the economics and organisation of manufacturing, particularly with regard to location and scale*' [1].

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The project's own working definition of RDM is: "Redistributed manufacturing is the **localization** of the design and production of manufactured artefacts, especially through the use of **small-scale** and innovative production methods and associated business models, which has the potential to benefit a region's **economy, society and environment**, and to improve its **resilience** to future megatrends such as climate change and globalization of supply networks". Under the umbrella of RDM could arise: new business models, new manufacturing technologies, new skills, and the use of new materials. RDM could also involve bringing back traditional making skills and use of traditional materials, but in a new way.

This paper presents an initial scoping of the societal level issues and potential impact associated with RDM, in relation to the resilience and sustainability of a region.

1.1 Definition of Terms

For this project we take "manufacturing" to be the creation (or repair, or remanufacture) of tangible artefacts from raw materials and/or parts, but not including the following: construction of infrastructure, utilities, design (when not connected with manufacturing), software, mining and minerals, and agriculture. We take the term "disturbances" to include short-term shocks (e.g. lasting from a few hours to a few weeks) and long-term stressors (which build up over months or years), both of which can affect a city-region and its manufacturing sectors. Disturbances can come from within the region (e.g. social unrest, industrial accidents) or from outside the region at national, EU or global levels (e.g. climate change, global recession, resource scarcity or price rises).

There are many terms that are used in relation to the broad concept of "resilience", including "vulnerability", "adaptive capacity", "robustness", "anti-fragility" [2]—all of which are '*different manifestations of more general processes of response to changes in the relationship between open dynamical systems and their external environment*' [3]. The term "sustainable" as applied to urban areas has also been assigned many interpretations by different authors, including: low CO_2e emissions, low waste generation, management of natural systems to ensure their long-term health, good air quality, and good quality of life for citizens that includes access to jobs, housing, etc.

For this project, we have defined two types of sustainability and two types of resilience, which were formulated to reflect these issues in relation to a city-region and its manufacturing sectors.

Economic Sustainability—Local taxes and grants from central government are sufficient to maintain a good quality of civic life, infrastructure, and to support businesses; citizens can be economically self-reliant; businesses can attract investment.

Environmental Sustainability—The regional natural environment is viable in the long-term and able to provide natural services such as drainage, manageable water courses, productive soil, healthy forests, good air quality, low levels of toxins, etc.

Short-term Resilience—Public and private agencies are able to establish normal services and economic activity soon after short-term economic, social, political, or environmental shocks that disturb public services and/or supply networks.

Long-term Resilience—The regional manufacturing sector, economy, and society as a whole is able to evolve and adapt in response to a range of long-term stressors. This evolution will likely look like '*constant change rather than stability*' [4].

In theory, there are many potential beneficial links between RDM and the sustainability and resilience characteristics of a region. These include improving the **productivity** of local manufacturing both in terms of labor and materials; reducing the **environmental impacts** of manufacturing; allowing the use of new **materials** or existing materials to be used in a new way—which could reduce dependence on global supply networks; providing **new jobs** for lower-skilled workers, improving social equity and social resilience; improving the **supply resilience** of a region through producing more locally; reducing the **lifecycle environmental impact** associated with consumption of goods and services in a region; and improving the overall **economic sustainability** of a region through increased diversity and innovation.

To explore these hypotheses, RDM must be viewed through at least two lenses: (i) the impact of the sustainability and resilience of the city-region, and of short and long-term disturbances, on the manufacturing sector; and (ii) the impact of the manufacturing sector on the resilience and sustainability of the city-region, especially in the face of disturbances. This is because RDM could be part of a solution to improving a city-region's resilience in general (i.e. the left view), but at the same time, the viability of manufacturing sectors and the growth of RDM will partly depend on the health of the local city-region (the right view).

2 Research Objectives and Methodology

One of the RDM|RSC project objectives is to contribute to the long-term research agenda for RDM, which includes carrying out a high-level scoping of the issue of RDM within a region. This paper is focused on the exploration of the effects of disturbances, past and future, on the city-region and its manufacturing sectors, and the need of the project team to develop an effective, comprehensive, and systemic approach to the task of scoping this issue within the project timeline.

Much research is being done on the resilience of urban areas, including: socio-technical resilience to climate impacts, social and ecological resilience, city resilience, economic resilience of regions [4], and industrial resilience. Bristol has a Strategic Resilience Officer and is one of the Rockefeller Foundation's 100 Resilient Cities (www.100resilientcities.org), but the subject of manufacturing has not yet been strongly included in its resilience work. Similarly, there has been a great deal of research on the concept of a sustainable city, including: the "sustainable city" as an oxymoron [5], sustainable development and carbon control in urban redevelopment [6], and the urban politics of climate change [7]. Papers on sustainability appear to be more likely to question the feasibility of the proposition when compared to those on resilience, possibly due to the fact that the idea of resilience aligns more with standard practices of business continuity planning and risk management.

Since the scale of the project brief is at the regional and societal level, there is a need to consider a wide range of technical and social issues in relation to each other. One established approach to research at the societal level is Integrated Assessment (IA), which has been used to carry out comprehensive assessments of, amongst many other subjects, the impact of climate change on urban areas [8]. IA has been described as '*the interdisciplinary process of integrating knowledge from various disciplines and stakeholder groups in order to evaluate a problem situation from different perspectives and provide support for its solution*' [9]. It takes a comprehensive, systemic approach which includes '*the needs and concerns of communities and industries, as well as the environment*' [10]. For example, the IA approach enables urban planning researchers to '*re-frame the questions that are asked so as to link global, regional and local scales and their interactions in the context of future urban planning*' [8]. Whilst a full IA is out of the scope of the RDM|RSC project, the principles of IA can be used to bring structure to what could be a rather unwieldly research agenda. This structure can inform and contextualize the design of any case studies and help to relate case study results to the overarching research agenda.

The next section describes the application of the principles of an 11-step process for carrying out an IA, as defined in [10], in the RDM|RSC project. The IA steps are quoted in bold italics, along with the work done to address them.

3 Integrated Assessment Steps

Step One: **'*Clearly identify the aims and objectives of the integrated assessment, including stakeholders and potential audiences for the results and any other products of the IA*'** [10].

The study **purpose** is to address the following research questions: (i) What could be the benefits of developing a systemic and dynamical understanding of relationships between a city's resilience and sustainability, and its manufacturing sectors?; (ii) For whom would these benefits be developed?; (iii) What metrics would be most useful to stakeholders in terms of informing their decision making?; (iv) How could an understanding of dynamical relationships be helpful for the RDM agenda and sustainable manufacturing in general?; (v) What qualitative and/or quantitative methods could deliver such an analysis within a reasonable time frame?

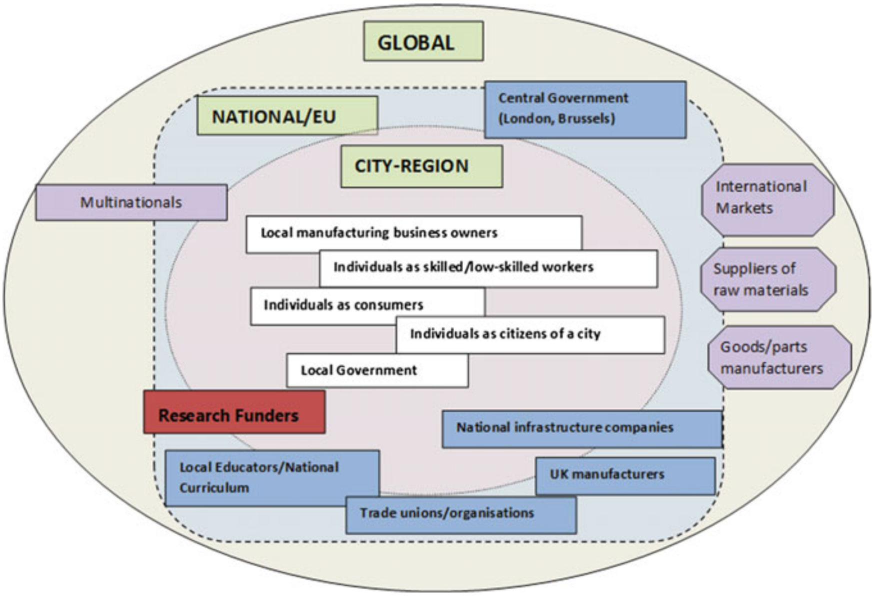

Fig. 1 RDM|RSC Research Stakeholder Map, with stakeholder groups (or roles) positioned according to their activities within the city-region, national/EU, and global realms

The **aim** for the IA is to meet this purpose in a way that is comprehensive and theoretically well-founded.

The main **audiences** are: the funding body (the EPSRC[1]), local government (e.g. Bristol City Council), and businesses in the Bristol area. Other potential audiences include: other cities, UK central government policy makers, the sustainable manufacturing community, the research community working on resilience, and those who might gain work in manufacturing. Figure 1 presents a stakeholder map for the research and where stakeholder activities are carried out in relation to the city-region, national/EU and global spheres.

Step Two: ***'Build an understanding of the constraints and issues in the case study as well as possible targets and measures of system performance'*** [10].

The key practical constraint is the limited project timeline and budget coupled with the need to consider a very wide ranging subject that is highly complex. The key developmental constraint is the unavailability of data on regional manufacturing activities.

A STEEPLE (Social, Technical, Economic, Environmental, Political, Legal, and Ethical) analysis of key system elements, including measures of system performance, and short and long-term disturbances, was developed by the project team. The STEEPLE development was based on the team's knowledge, network

[1]The UK's Engineering and Physical Sciences Research Council (www.epsrc.co.uk).

meetings, local and national risk registers, discussions with experts, and a review of literature.

Key system elements include: workforce skills and education, levels of unemployment and inequality, automation, manufacturing technologies/machinery, demand for goods, costs of materials/parts/energy, number of start-ups, waste generation, emissions (e.g. CO_2, NOx, SOx), rules on international trade, UK Government support for innovation, environmental laws, employee legislation, labor/environmental standards, and obligation to future generations.

Short-term disturbances include: pandemics/changes in workforce, social unrest, changes in availability and/or cost of materials or parts, technology disruption, availability of investment capital, economic downturns/upturns, extreme climatic events, shifts in weather patterns, sudden changes in political landscape, changes in supply chain legislation, changes in business ownership, and shocks that change ethical stances.

Long-term disturbances include: changing demographics, globalization and future markets, scarcity of resources, mass customization, dynamic technology and innovation, climate change, global knowledge society, and the role of global non-profit and philanthropy organizations [11].

Step Three: **'*Develop an initial conceptual framework, identifying key drivers, including management and development options as well as state and utility variables and their interactions*'** [10].

An initial conceptual framework for the research was developed by the project team. This was partly based on data gathered during the STEEPLE analysis and partly on the Press-Pulse Dynamics framework from Collins et al. [12]. This framework sets disturbances in context, in relation to an ecosystem and the human systems that live within it; it defines a "press" as a long-term stressor, such as sea level rise, and a "pulse" as a discrete event that rapidly alters ecosystem function. While Collins et al.'s framework is designed to enable discussion of human-ecosystem interactions, we have applied it to the discussion of the environment in which manufacturing operates. Thus, we interpret presses as manufacturing mega-trends (taken from the Factories of the Future Roadmap [13]), and pulses as short-term risks to the city, its residents, and to economic activity (taken from national [14] and local risk registers [15]). The Pulse-Press Dynamics framework also uses the terms "structure" and "function", which are used in the field of ecology to differentiate between the core components of an ecosystem and the suite of processes that occur within the ecosystem [16]. We use these terms to distinguish the structural (e.g. infrastructure) elements of the manufacturing and economic/social systems from the functional ones.

Figure 2 presents a first version of the RDM|RSC research framework. On the right, the local manufacturing template includes the structures that enable manufacturing, and the ongoing functions carried out by manufacturers. In the middle, the manufacturing "environment" incorporates the local biophysical environment and social/economic systems. Key parts of this manufacturing environment are

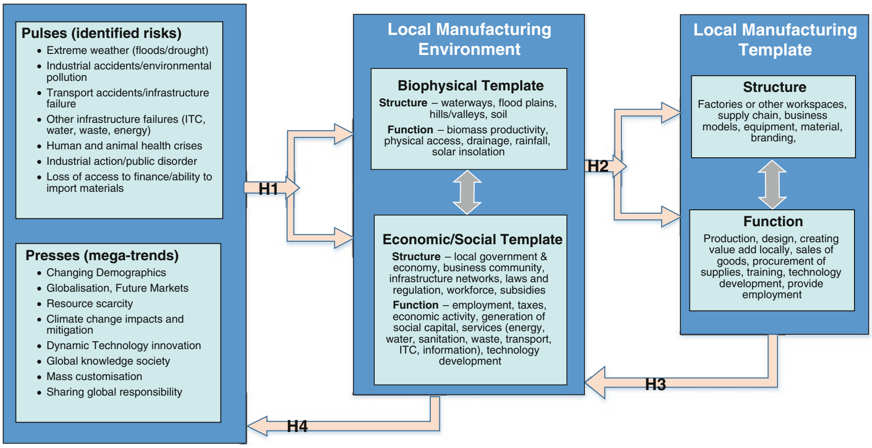

Fig. 2 Research framework for exploring the impact of disturbances on the city-region and its manufacturing sectors

assigned as structure or function. On the left, the key pulses and presses that have been identified so far are named.

Four integrating hypotheses are represented as arrows in the diagram.

H1: Pulses and presses from inside the local environment (e.g. public disorder) or from outside (e.g. loss of access to finance) can affect both the structure of the environment and/or the functioning of the environment. The more resilient and sustainable the environment is, the more easily systems will be able to regain normal functionality after a pulse and/or continue to function under the pressure of various presses.

H2: The dynamics of structure and function within the manufacturing sector are dependent on and highly influenced by changes in the environment in which it operates, including the biophysical structure and functions, and the economic and social structure which provides essential services and infrastructure—such as the supply of materials and parts for different types of manufacturers. Some of this functionality, in economic terms, can be seen as adaptive '*collective agency*' [17].

H3: The activities of manufacturers—including creating jobs, designing new products and services, adding local value—and the structures developed to support manufacturing activity affect the local environment through adding to the tax base, creating social capital, toxic emission, creating demand for infrastructure, etc.

H4: The way the local environment is managed, the way that human activities are carried out, and the way that the local economy and society is managed can have an effect on the severity or likelihood of pulse events. For example, social unrest is more likely if there are chronic societal problems; infrastructure failures are more likely in an environment that is less economically resilient.

Step Four: **'*Workshop the initial conceptual framework and general scenarios with stakeholders*'** [10].

The framework presented in Fig. 2 was converted into a "strawman" Causal Loop Diagram (CLD) by the project team. CLDs are '*visual representations of the dynamic influences and inter-relationships that exist among a collection of variables*' [18]. CLDs can help by quickly capturing hypotheses about the causes of system dynamics, eliciting and capturing the mental models of individuals or teams about the system, and communicating important feedbacks [19].

The strawman CLD (Fig. 3) was presented to groups of participants in a workshop, with the intention to stimulate debate about the interrelationships between system elements, evaluate which elements might be missing (or superfluous), and think about what the role of RDM might be in future. Workshop participants were members of the project's network, from a variety of backgrounds including academia (e.g. economists, engineers, climate scientists), manufacturing, local government, and citizens.

Each of the workshop groups came up with a wide variety of additions and changes to the model, with some groups focusing on a particular manufacturing sector. There was lively discussion about the nature of resilience and sustainability in a region, the resilience of certain manufacturing sectors such as aerospace, industries that had once thrived in Bristol but failed to survive globalization, the potential role of new technologies such as Additive Layer Manufacturing, and more philosophical observations about the role of manufacturing in our society.

Several themes emerged during a general discussion with participants, including: The **future of work** and the quality of jobs: if new technologies create high levels of productivity in some industries and new skill requirements, how will employment polarization between those who have good jobs and those who have poor or no jobs at all be avoided? The cultural **distance between society and the physical**

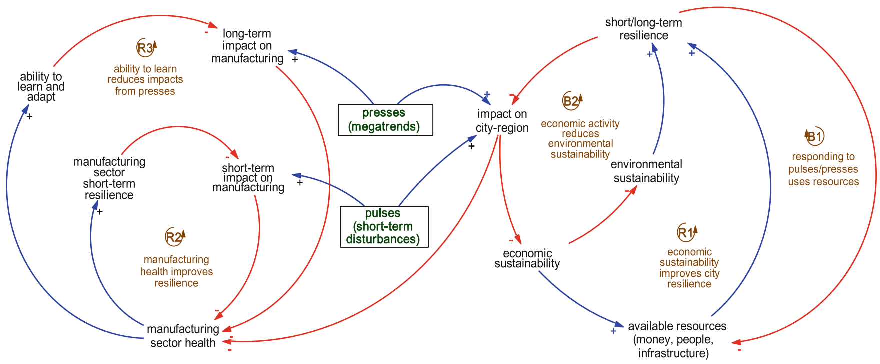

Fig. 3 "Strawman" causal loop diagram representing theories about causal relationships between different types of resilience and sustainability, and the manufacturing sectors, as presented to Workshop Participants (Positive causation is represented by *blue arrows* with a "+" sign, and negative causation is represented by *red arrows* with a "−" sign. Balancing (i.e. goal seeking) loops are named B1, B2 and reinforcing (i.e. growth) loops are named R1, R2, R3.)

realities of manufacturing: manufacturing is increasingly done in the virtual design world, which limits our appreciation for physical limitations and materials—the key to sustainability and resilience. The relationship between pulses and presses: since people in general are poor at dealing with long term trends so **pulses are what comes to matter** to organizations and what they respond to. The desire to increase prosperity encourages the reinforcing of "**local for global**" innovation, and the desire to sustain manufacturing in the face of strong presses encourages "**local for local**" innovation. **Time is a critical factor** in the model; the model is dynamic and moving, not static, and has emergent properties. For example, as skills develop within certain industries, that will generate new, innovative businesses, possibly previously un-thought of.

Further Work, Steps Five to Eleven: The remaining seven steps in the IA process will be done during 2016 and will conclude with a distribution of the results to relevant stakeholders and user groups. This work will include: (i) researching what data exists regarding manufacturing in the region (e.g. physical production, material flows, and waste flows), and establishing suitable dimensions and time scales for mapping manufacturing and making in the region; and (ii) planning the development of a dynamic, systemic, and simulatable model (or set of models) that could represent the combined understanding from the workshop participants and findings from a wide range of reports and data analysis, and could be used to test different "what if" scenarios for RDM in the future.

4 Discussion

In terms of methodology, use of the IA approach has been valuable as a formal process for exploring a very wide-ranging and complex sustainable manufacturing issue. The research so far has found that causal loop diagramming is an appropriate method for starting to think about dynamic relationships between the key research issues at the societal level. Later steps in the IA will choose one or more formal systems modeling methodologies. System dynamics [19] would be suitable for creating insight into the interrelationships between the different resilience and sustainability characteristics of the system. Event-driven modeling could be added to a system dynamics model to represent pulses and presses (e.g. Schieretz and Grossler combined system dynamics with agent based modeling [20] to examine supply chain structures). Agent-based modeling could also be appropriate, since much of the potential for RDM is likely to be actualized by innovative businesses of different sizes and types.

In terms of findings, several apparent dichotomies and conundrums within the research agenda have already been identified, and these will be explored in more depth as we move forward with the IA steps. These issues include:

Timing of organizational response: Are cities and organizations likely to anticipate long-term changes (presses) or are they more likely to wait until there are short-term shocks (pulses) that impact their operations?

Modeling physical flows: Due to a lack of data, it may not be possible to model, even at a very high level, the flow of materials into and out of the region, or the amount of physical manufacturing that is being done. It may, however, be possible to understand these issues for a few companies and their practices through case studies.

Divergent characteristics: There are boundary issues with the four concepts of resilience and sustainability, as defined in Sect. 1. For example, is a company that stays in business resilient even if does so by sending production jobs overseas? Knowledge economy jobs could be considered preferable to production jobs since they provide economic gain with lower environmental impacts, but how do they affect the resilience of the region in terms of supplies of physical goods?

Heterogeneity in manufacturing: Ideally, we could consider the historical performance and future potential of a wide range of manufacturing entities in the region, in terms of size, sector, and technologies used—from a single person making musical instruments, for example, all the way up to a huge aerospace manufacturing plant—since they all may have potential for introducing RDM. Can this variety be included in a model in which elements are aggregated, and how would potential for RDM be limited by the type of manufacturing being done and materials used?

Skills and jobs: High-value RDM could contribute a great deal to economic sustainability, but what are the implications for lower-skilled workers? Unless the skills of the local workforce are updated to meet the demands of implementing RDM, it may not solve the persistent unemployment problem that has existed in some parts of the city since several large factories closed down.

Uncertainty about disturbances: The size of uncertainty in terms of future presses and pulses is very large. This could be felt in changes to the nature of commerce, the nature of work, availability of materials, international logistics and trade, the role of technology in manufacturing, amongst many other changes. Will it be possible to even model a “what if” scenario that includes such levels of uncertainty? How much will the future look like the past?

Location of impacts: It’s possible that whilst reshoring of jobs is one of the expected benefits, reshoring could re-import the environmental impacts associated with production that are now offshored. Is the city and the business community prepared to invest in minimizing these negative impacts?

Making use of opportunities: In addition to hazards, there could be many opportunities inherent in the range of future presses and pulses. What types of RDM can make the best use of them? What types of networks and social connections can be utilized to create appropriate responses in the local economy?

5 Conclusions

The research agenda for the RDM|RSC project presented a need for an approach that could explore the potential for re-distributed manufacturing at a societal level and link it to the issues of resilience and sustainability within a region. This requires viewing RDM as both dependent on regional sustainability and resilience, and influencing it.

The approach of Integrated Assessment was applied to help deal with the wide range of subjects and issues involved, and to investigate the dynamic complexity of systems. Research objectives, a stakeholder map, and a research framework were developed as part of the IA. The research framework makes use of concepts from ecology, naming disturbances as "pulses" or "presses", and conceptualizing the local biosphere and social/economic systems as making up the environment in which manufacturing is done.

A "strawman" causal loop diagram, representing a theory about the relationships between different types of sustainability and resilience and manufacturing, was presented to several groups of workshop participants. The workshop discussions revealed several apparent dichotomies and conundrums within the research agenda, which will be explored in more depth as the research continues. The approach so far has opened many "cans of worms" and it is anticipated that through the rest of the research project we will rely on our network of experts and manufacturers to be part of the modelling process and inform the research so that it remains relevant and useful to both the sustainable manufacturing community and research policy makers.

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The Local Nexus Network: Exploring the Future of Localised Food Systems and Associated Energy and Water Supply

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Abstract The Local Nexus Network is addressing the intersection of two important emerging research areas, re-distributed manufacturing and the food-energy-water nexus. It is an on-going initiative which aims to develop an evidence-based comprehensive research agenda and foster an inclusive community of researchers and stakeholders for sustainable local food-energy-water nexuses. This paper presents the conceptual framing for understanding the challenges of

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local nexus, reports empirical findings around a particular case study, and makes initial reflections on the research and practical challenges and opportunities.

Keywords Re-distributed manufacturing · Food-energy-water nexus · Food system · Energy consumption · Water footprint

1 Introduction

Historically, human industrial and economic activities have been greatly shaped by the patterns of resource use in favour at the time. For thousands of years pre-1800, material and energy resources, mostly renewable, were extracted and used locally. The widening exploitation of energy-dense fossil fuels, in post-1800 industry has resulted in more centralised production. This is primarily based on geographically concentrated resources which are accompanied by large scale distribution infrastructures. Whilst the scale economies of these large and concentrated systems have served us well in certain respects, continued reliance on centralised resource extraction and production has contributed to the formation of a range of acute issues facing global society today, such as insecurity of essential resources, climate change, and social- and spatial-economic imbalance and injustice.

Driven by the desire to improve resource use and broader sustainability in response to the above issues, changes towards 're-distributed manufacturing' have been considered, to explore the future of localised production with indigenous sustainable resources to support the local economy and communities [1]. Among products and services that can potentially benefit from localised production, food represents one of the most essential commodities for every society. Furthermore, it has increasingly been recognised that close ties exist between food production and manufacture (i.e. processing) and energy and water. This is manifested by (i) the significant energy and water footprints in food production and processing and the mutual footprint between energy and water systems (e.g. [2, 3]), (ii) their intertwined connections with land and broader ecosystems, and (iii) the potential for more localised sources of energy and water supply alongside local food production. The inseparable challenges of food, energy and water, and especially within the context of climate change, have been referred to as the "perfect storm" [4], requiring an integrated and holistic approach as opposed to tackling them in separate silos. This understanding, conveyed via the "nexus" concept, has gained momentum in the last few years through several key reports from international organisations such as the World Economic Forum [5] and the UN ESCAP [6] and events such as the Bonn 2011 nexus conference (http://www.water-energy-food.org/).

Studies of the food-energy-water nexus in combination with localised production are still relatively rare, although emerging [7]. The Local Nexus Network (LNN) (www.localnexus.org) is an on-going initiative which aims to develop an evidence-based comprehensive research agenda for sustainable local nexuses, by conducting preliminary research to establish an initial framework for understanding this area and to identify the significant research challenges. The project encompasses the important aspects of engineering technology and systems for food processing and energy/water supply, business models and supply chains, governance and whole-system integration. The purpose of this paper is to present initial results and thinking developed from the LNN so far, including (i) approaches to understanding re-distributed food systems and the local nexus as a whole, (ii) empirical findings around a particular case study, and (iii) a preliminary discussion on the challenges and opportunities for research and practice.

2 Conceptual Framing of the Local Nexus

Much of the complexity of the food-energy-water nexus stems from the interactions between these systems components. Multiple perspectives, held by different stakeholders and research contributors, add to this complexity, but are all important for understanding and improving the nexus interactions. Therefore, a *multi-layer structure* is adopted by the LNN, as summarised in Table 1. According to this structure, a nexus system can be intellectually approached at three different, yet inter-connected layers, namely 'physical', 'socio-economic', and 'policy and regulatory'. Each layer is characterised by the actors present, activities or processes that take place, flows that connect the actors and activities, and performance indicators that should be considered from the perspective of that layer. While the content of Table 1 is more illustrative than definitive, this basic structure has helped to frame the discussions at various events organised by the LNN.

While the above layered structure can be applied to the nexus at any spatial scale, a separate supply-chain conceptualisation, namely *food system configuration*, was proposed. More specifically, activities in a food system are considered to be distributed around and between two focal points, *farm gate* and *plate*. A food system configuration for a specific food product is characterised in the first place by the geographical location of the activities that take place before the farm gate (i.e. agriculture) and those between farm gate and plate which includes all the manufacturing and distribution processes. Waste processing activities are also included after plate to allow for the consideration of resource recycling and reuse. Relative to the location of plate (i.e. point of consumption), these food system activities may be termed local, regional, national or international. Another important characteristic of a food system configuration is the nature of the plate, i.e. the types of consumption, with distinctions made between household, institutional (e.g. schools, hospitals), and commercial catering. This distinction allows consideration of the differences in volume, variety, and mode of serving which may have an impact on the choice of processing/logistical options and locations.

Table 1 Layers for understanding the nexus

Layer	Actor	Activity	Flow	Performance indicator
Physical	Factory, equipment, vehicles, land/ecosystems	Production, transport, storage	Material, energy	Process efficiency, flexibility, safety; product quality; environmental impact
Socio-economic	Businesses, employees, consumers, communities	Business planning and management, trading, purchase	Money, information	Profitability, affordability, security of supply, social acceptability
Policy and regulatory	Policy makers, executers, targets	Policy making, execution, evaluation	Information	Degree of meeting policy goals, maintenance of public goods

3 A Case Study on Bread

Guided by the above conceptual framing, a case study on bread, referring specifically to the city of Oxford, UK, where data are available, has been initiated to contribute to the understanding of the functions and the future directions of the local nexus.

3.1 Bread for Oxford: The Current Configuration and Its Shaping Factors

Located in south central England, Oxford has a population of 158,000 people (June 2014). Because the food retail market and supply chains are relatively homogeneous and mature in the UK, it is fair to assume that the manner in which food is provided to Oxford is similar to that for the country as a whole: 90 % of food retail outlets are 'multiples' (i.e. chain stores) with centralised supply and distribution systems [8]. The majority of the remaining independent retail outlets are also supplied by wholesalers using centralised distribution systems. Thus the extent to which Oxford is directly supplied with manufactured foods from local sources (for example, from within the county of Oxfordshire) is very small, estimated at around 1 % by value. This is likely to be through a mixture of independent retailers, bakers, co-operative stores, and local markets.

Within this context, further details can be explored on bread production and consumption in connection to Oxford. Assuming that Oxford's citizens consume bread at the national average rate, it is estimated that approximately 4990 tonnes of bread is sold every year through retail outlets for home use, 210 tonnes of bread is consumed out of the home in the form of sandwiches, and 40 tonnes is used in restaurants and catering outlets [9]. In total this equates to an annual consumption of

6.5 million standard 800 g loaves of bread, or 41 loaves per person per year. Around 78 % of the £1.6bn UK bread retail market is accounted for by sliced packaged bread from centralised plant manufacturing, sold through retail chains. Of this plant manufactured bread, 75–80 % is produced by three large firms, each of which have around 10 bakeries spread across the UK, producing a variety of baked goods in addition to bread [10]. Thus the main thrust of the bread supply to Oxford can be considered to come from baking facilities that have a degree of regionalisation, but which cannot be considered 'local' to their place of consumption, if the 'local' scope is, as assumed in the case study, limited to the county of Oxfordshire.

In addition to sliced, packaged bread, another 17 % of bread (in terms of both value and tonnage) comes via 'in-store bakeries'. These bakeries, often within supermarket outlets, are normally a combination of loaves baked 'from scratch' (i.e. fresh from raw ingredients) and 'bake-off', where a frozen, part-baked loaf from a centralised manufacturing facility is put into ovens locally for the final stages of baking. This 17 % may therefore be considered to have a degree of localisation in manufacturing, although the exact split of scratch vs. bake-off is not known. The final 5 % of bread by value is from artisanal bakeries where bread is produced on a smaller scale with a lower degree of mechanisation. Because these loaves are often sold for a higher price, artisan baking accounts for only 3 % of the market by volume. Thus if it is assumed that scratch baking in store accounts for 10 % of the market, then some 13 % of bread in Oxford might be considered locally baked.

Besides baking, the other main manufacturing stage in the production of bread is the milling of grain into flour. Although 20 % of wheat grain is imported from outside the country, the vast majority of actual milling activity occurs within the UK. Import of grains is considered a technical necessity by the baking industry as wheat grown overseas has a higher percentage of proteins that are critical in baking. Flours used commercially are often a mixture of UK and imported flours, blended to achieve the correct protein level for the customer [11]. There are around 50 commercial-scale flour mills in the UK, producing for both national and regional customers, plus export markets. Although there are a number of commercial mills located in Oxfordshire, several of which sell their products locally, none of them sell to an exclusively local market, thus it is questionable whether they would be considered to be in and of themselves an example of 'local' food manufacture as described above. Nonetheless, craft bakers in and around the city of Oxford do purchase flour directly from these mills, thus constituting part of a local food supply chain. This is reinforced by the local procurement of grain by some of the mills, who have long-term relationships with nearby farmers.

Seen overall, and compared to other products, the current configuration of milling and baking for Oxford's bread supply can be thought of as a predominantly regional/national activity, accompanied by a less significant yet visible local portion.

3.2 Possible Re-Distributed Futures

The current geographical configuration of Oxford's bread system is not the only one imaginable. As described above, bread supply in the past would have looked very different; and in other parts of Europe it still does because of historical and institutional legacies and different food cultures [12]. In France, for example, local craft bakeries have 55 % market share, compared to 5 % in the UK. In Italy they have 85 % market share [13]. In France, although large millers dominate flour production, there are also a larger number of small to medium mills, partly due to historical production quotas restricting expansion. If Oxford's bread provision looked more like one of these countries, the city would need many more bakeries, and many more bakers. The shift from a centralised, highly mechanised process to a more labour intensive style of baking would initially cause a lack of skilled labour. The high cost of renting appropriate floor-space for bakery units would also be challenging. Both labour and rental costs would be passed on to customers, so a cultural change is also implied in that consumers would have to be prepared to spend more. In return, consumers would benefit from fresher bread, potentially with fewer of the additives normally used to lengthen shelf life, and potential for a greater degree of social interaction with the source of their food and other consumers. The recent growth in value of the artisan bread sector by 10.8 % between 2009 and 2014, despite the fall in volume in the bread market overall, shows that many consumers are not motivated solely by price [14].

But a French or Italian model, with large numbers of independent artisan bakeries, is not the only way of reconfiguring bread manufacturing. Supermarkets could bake a higher proportion of bread in their stores. There could be a single highly automated factory on the outskirts of the city producing bread to be sold through multiple retail distribution channels, bringing localisation but preserving some of the economies of scale found within the current model. At one extreme end of the spectrum, a large percentage of the Oxford population could use bread makers to produce their daily bread in their own houses. Such changes would most certainly have a significant impact on the bread manufacturing sector, and there are other examples of more localised production displacing centralised production. Craft brewing, for example, where beer is produced on a small scale with often labour-intensive processes, is now significant enough that larger beer manufacturers feel threatened by this emergent market sector.

The implications of the localisation of food manufacturing activities will differ depending on the market environment and its governance. The RDM model suggests the emergence of market complexity that allows large mass production to co-exist with small scale, niche productions. Such product market segmentation rests on different models of production and creates demand opportunities that often expand demand. The key challenge to the redistributed manufacturing model in bread remains the ability to segment the market to juxtapose a supply that competes on price and reliant on scale economies in large scale manufacturing operations, with more locally produced small-scale operations which aim to win on product quality and variety. It should also be noted that a scenario in which there are more smaller bakeries than in the current configuration, but where they remain owned by a small number of large companies, will result in very different socio-economic considerations than a scenario in which ownership as well as physical manufacturing facilities are distributed.

3.3 Energy Consumption

Several studies exist on the energy consumption for part or the whole of the life cycle of the production of standard bread in the UK. In a work published in 1980, Beech [15] estimated the primary energy consumption for growing bread wheat to be ca. 4 MJ/kg bread (out of the total consumption of ca. 15 MJ/kg bread for wheat production, milling, baking and keeping in shops), which is significantly higher than 2.5 MJ/kg wheat, an estimate for standard bread wheat growth from a more recent study by Williams et al. [16]. The latter work also presented an estimate of 1.7 MJ/kg for organic wheat, which despite the lower yields, higher inputs into fieldwork, and up to 200 % more land needed still requires less energy input than standard wheat because of the avoided use of synthetic nitrogen fertilizers.

Among the manufacturing steps, the baking process appears to be most energy-intensive. Beech [15] estimated the primary energy consumption of standard industrial making to be ca. 7 MJ/kg bread. In comparison, the Carbon Trust study [17] analysed actual annual energy data for 13 bakeries, and the following energy intensities were calculated based on the amount of delivered energy a site uses each year and its annual production, with estimates of 551 kWh of fossil fuels (predominately gas) and 218 kWh of electricity, per tonne of product. Assuming a 35 % conversion rate from primary energy to electricity, this is approximately 4 MJ/kg bread of primary energy, which is very close to the estimate from a European study by Le-bail et al. in 2010 [18].

It appears that the more recent studies have shown a greater energy efficiency across the life cycle of bread production, which may be attributed to improvement in technology and practice. More interestingly for re-distributed manufacturing and in relative terms, Beech [15] concluded that compared to industrial baking, energy consumption of home baking could be lower if sufficient oven loading (e.g. 2–3 loafs of 670 g each per batch) is adopted and gas is used as the fuel; the efficiency can however drop significantly with lower loading levels and, regardless of the loading level, with the use of electric ovens. Le-bail et al. [18], on the other hand, compared the energy demand in conventional bread baking with that in the processing of frozen part-baked breads—the option of the bake-off operations as mentioned in Sect. 3.1—and concluded that the part-baked process demands about 2.2 times as much energy as the conventional bread making process.

3.4 Water Footprint

Water is required in all the bread manufacturing steps including agriculture (i.e. wheat growing), the milling process and bread making. Water used growing wheat accounts for over 95 % of lifecycle water use of bread in the UK [19]. During the milling process, water is added to soften the wheat, making it easier to process. Based on the information collected from two mills in Oxfordshire, the amount of water used within the process is approximately 1 % of total wheat by weight. For baking bread, water is combined with flour to form a dough and accounts for the second most important ingredient by weight (i.e. around 36 %) after flour as the main ingredient. While water is the second most important ingredient of bread making process, the total water used in baking bread is insignificant compared to the amount used for growing wheat. However, the water used during all stages of manufacturing (i.e. milling and baking processes) needs to be as high quality as drinking water. Both milling and baking companies interviewed in the Oxford area reported they use mains water to supply the necessary water for their processes. This is because mains water is easily accessible and drinking water quality is regularly tested and rigorously checked by the UK water companies and Drinking Water Inspectorate to ensure drinking water standards are met [20].

The global average water footprint for wheat bread is 1608 m^3 per tonne [21]. Water footprint is categorised into blue, green and grey water. Blue water footprint and green water footprint refer to the volume of (i) surface and groundwater and that of (ii) rainwater consumed, respectively. Grey water footprint is defined as "the volume of freshwater that is required to assimilate the load of pollutants based on existing ambient water quality standards" [21]. The global share of these categories in wheat bread production is estimated to be 70 % green water, 19 % blue water and 11 % grey water. Due to the climate in Oxfordshire, wheat is not irrigated (i.e. uses no blue water) and is a rain-fed crop over the length of growing period [21]. The global average water footprint per tonne is similar in either irrigated or rain-fed agriculture [22]. However, as the UK wheat yield is amongst the highest in the world [23], the water footprint of wheat bread in Oxfordshire substantially reduces to 524 m^3 water/tonne of bread, based on the data between 1996 and 2005 [21], with 74 and 26 % in green and grey water, respectively.

Based on regulations set out by the Environment Agency (EA), water abstraction for more than 20 m^3/day from either a surface or an underground source needs an abstraction licence (although some cases such as trickle irrigation are exempt) [24]. An analysis of the EA's data [25] for Oxfordshire shows little restriction on water abstraction in this region. Based on interviews with local milling and bakery businesses in Oxford, the water they use in manufacturing is supplied via mains water at present, and consequently it has energy embedded in it as a result of this water being abstracted, transported, stored, treated and distributed to their premises by the water company (Thames Water). As their water demand is less than the threshold of 20 m^3/day, an abstraction licence would not be required if these businesses decided to opt for direct abstraction from a local surface or groundwater source. However, locally sourced water (as distinct to mains drinking-quality water) would need to be pumped, stored and treated before being used in milling and baking. These steps are energy demanding and need further analysis in relation to water and energy nexus issues.

4 Opportunities and Challenges of Local Nexus: Initial Reflections

Through the bread case study presented above, another case study on tomato paste currently being undertaken and several information-gathering stake-holder workshops in autumn 2015, an understanding of the opportunities and challenges of creating a local nexus in food processing is forming.

The potential opportunities of applying the RDM model to the food system needs to be articulated with a broader understanding of the different elements of 'value' associated with food and hence desired functions of the food system. In relation to the physical layer (Table 1), food is valued as the means to provide a secure and balanced supply of nutrition, without compromising the ecosystem and the environment. In the socio-economic layer, the food processing industry is a major sector expected to bring economic value to businesses as well as the workforce. In both aspects, it is widely accepted by the stakeholders that balancing *equality*—between different sections of society, between humans and nature, between businesses, and between businesses and consumers—and *efficiency* is highly desirable. Furthermore, food plays distinct social and cultural roles in human society and helps to enhance the healthy connections between human and nature, and within local and urban communities.

The positioning of these values and functions has allowed a range of potential benefits and opportunities for a more localised food system to be considered. In the physical layer, food may be a higher quality through improved freshness, personalisation and customisation. Safety risks and waste may be reduced due to the shortened supply chain. Furthermore, locally abundant resources, such as water or renewable energy, may gain utilisation in certain cases, and resource recycling and reuse (e.g. of nutrients) may be better promoted contributing to improved resource efficiencies. Socio-economically, it may lead to reduction of costs due to resource savings, promote the growth of small businesses and hence local employment. It may also offer an opportunity to allow people to rebalance between "cheap" food (as a consequence of the current large-scale centralised production) and stronger communities (possibly boosted via improved local employment and sense of community).

In parallel to the broad expectations on the positive contribution of a localised food system to the broader values and functions, a number of challenges have been identified. These relate to the various constraints within which the system could deliver its functions. Physically, increased local food production and processing means extra local demands for land, energy and water. Therefore, a rationally re-distributed food system should consider the location of its various activities (agriculture and processing) in conformation with resource availability, and avoid worsening any local "nexus" stresses. In the design of a specific system, possibilities of reusing energy and water within the food system and between different local economic sectors should be considered to ease any tension. When treated carefully, the nexus challenges may be turned into opportunities. Another category of physical constraints relates to the suitability of technology for smaller-scale operations and any additional handling introduced by re-distribution (e.g. processing of frozen part-baked doughs), where innovation is desired to enable such operations to be realised with an acceptable efficiency. There are other more practical constraints, such as dated manufacturing facilities and limited floor-space availability in urban areas, which need to be overcome to allow existing local food operations to expand and/or for brownfield sites to be reused and repurposed.

There are also socio-economic and regulatory challenges, which may emerge together with some of the opportunities presented earlier. For example, although localised operations may promote efficient resource utilisation, the potential loss of economy of scale may negate economic gains derived from resource savings. Also, while a localised food system may contribute to the building of stronger communities, equally there is a risk of creating a two-tier society in which local food businesses primarily serve an economically privileged sub-population with premium products, leaving the deprived rest to "standard" food supply. Similarly, the potential for increased local employment may be offset by the shortage of qualified workforce. On food safety, the challenge of establishing a proper regulatory framework to deal with a large number of small manufacturers may counter-balance the benefits of shorter supply chains. Such challenges need to be addressed to allow localised food systems to achieve their full potential.

5 Concluding Remarks

To facilitate the understanding of re-distributed food systems and the associated energy and water supply and use we have proposed a multi-layer framework and the notion of food system configuration. The empirical analysis of the bread production for Oxford city has revealed a mixed (national-regional-local) configuration of the current system, its historical shaping factors, and has begun to outline the potentials and techno-socio-economic implications of future, more localised configurations. The analysis of the associated energy and water use shows further resource and environmental implications of the current system and of the more distributed options. The initial learning from the empirical studies and from the collected opinions of stakeholders has crystalized into a number of potential opportunities and challenges of the local nexus. As the work of the LNN project continues, this learning will be broadened and deepened, with further insights to be gained on critical issues such as unification/integration of multiple values conceived for the food system, clarification of the semantics of the characteristic geographical scales (e.g. local, regional, etc.), and conceptualisation of multi-scale or mixed economies within which the role of more localised operations could be better articulated.

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Part IX
Invited Session 5: UK-China Forum on Innovation for Green Manufacturing

Application of Multilevel Maturity in Collaborative Development Mode of Aircraft

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Abstract Through reasonable modular decomposition of the tasks in life circle of aircraft development, a modular hierarchical structure of the aircraft development is established. According to the modular hierarchical structure, multilevel maturity in the development process is proposed. The maturity in the aircraft development is divided into N levels and the relationship between them is built, which make the maturity management more complete and unified. Then a comprehensive evaluation method of multilevel maturity is proposed by using the fuzzy comprehensive evaluation method combined with the multilevel maturity structure. Modular structure, multilevel maturity and multilevel maturity evaluation constitute the multilevel maturity model. Finally, an application case of the aircraft development process is given to illustrate the validity of the multilevel maturity model.

Keywords Module · Multilevel maturity · Evaluation of multilevel maturity

1 Introduction

Maturity is the level or extent of activities, which is used to describe the integrity and deepness of business process in product development. Collaborative development of an aircraft is imperative due to the high complexity of the aircraft product.

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Application of maturity is an important guarantee for the aircraft to achieve collaborative development [1].

Maturity model is a set of scientific system and method, which can used to characterize the status of activity development from junior to senior. The maturity model sets detailed standard and defines different levels for various stages of business process to describe the development situation, and the program could be adjusted based on the description. It can grasp the completion situation of aircraft development in general, provide the basis for process-driven engine development, shorten the aircraft development cycle, improve product development quality and reduce product development costs with the application of maturity model.

Currently, the research work about the maturity are mainly focused on project management maturity, technology maturity, design maturity, manufacture maturity, etc., and different models of the maturities are proposed [2–6]. There are many kinds of maturity evaluation methods, including qualitative evaluation and quantitative evaluation. Common evaluation methods are key process areas method, assessment questionnaire method, analytic hierarchy process method and comprehensive evaluation method [7–9] (Table 1).

However, the research of various maturities are relatively independent and have little relationship with each other, and the level partition and evaluation methods are different, which will imperatively bring some difficulties to the overall management of aircraft development process. To solve the above problems, the concept of multilevel maturity is proposed in this paper, which divide the maturity in the whole lifecycle of aircraft development into multilevel structure mode, and corresponding model and evaluation method of the multilevel maturity are also presented, which are applied to the aircraft collaborative development process to verify the validity of the multilevel maturity model.

Table 1 Comparative analysis of four kinds of evaluation methods

Evaluation method	Analysis form	Objectivity	Rationality	Evaluation efficiency	Accuracy
KPA	Qualitative	Inferior	Inferior	Low	Low
AQ	Qualitative and quantitative	Inferior	Inferior	Low	Low
AHP	Qualitative and quantitative	Little superior	Inferior	Low	Low
CE	Qualitative and quantitative	Superior	Superior	High	High

2 Multilevel Maturity

2.1 Modular Aircraft Product Development

Aircraft product development is an enormous systematic project, including market analysis, design, manufacture, test verification, test flight, technology research and project management. Therefore, it is not easy to manage and control the evolution of the development process. A modular structure of aircraft development is presented in Fig. 1 to make the lifecycle management of the aircraft development more effective. The system structure is divided into N levels that include many modules from top to bottom.

Generally, there are two processes in the modularization, which are module decomposition and module centralization [10]. Modular decomposition is to divide a complex system or process into some independent and half self-discipline subsystems based on some specific association rules. Module centralization is to unify some independent subsystems or modules into a more complex system or process according to some association rules.

It can refine specific responsibilities and tasks division of every department or person in the whole development process, and reduce the complexities of product development relatively with the modular structure of aircraft development.

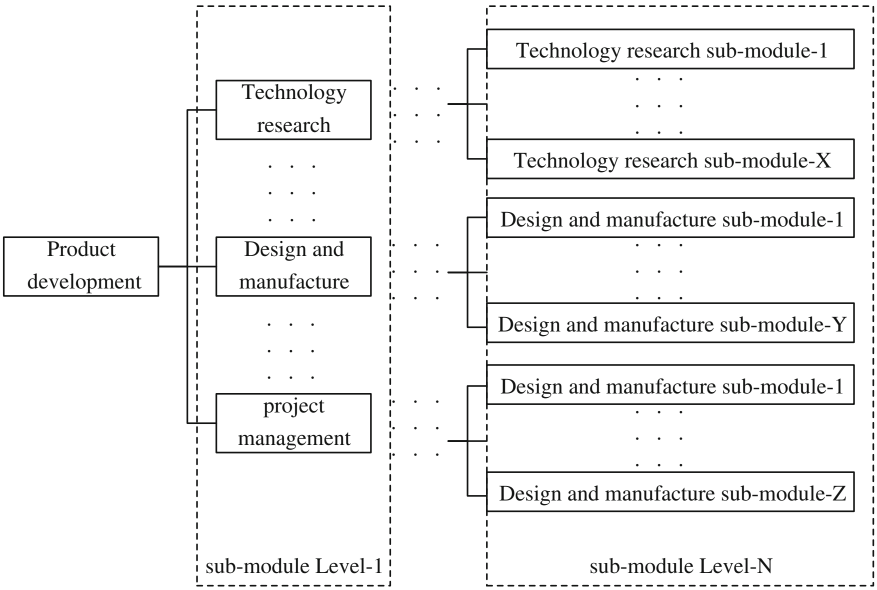

Fig. 1 Modular hierarchical structure schematic of product development

2.2 Multilevel Maturity

Many kinds of maturity can be applied in aircraft development, such as technology maturity, design maturity, manufacturing maturity, experimental verification maturity, effectiveness maturity, software capability maturity and so on. Based on the modular hierarchical structure of aircraft development, the concept of multilevel maturity in aircraft collaborative development process is proposed by dividing the maturity in the whole lifecycle of aircraft development into multilevel structure mode.

As shown in the Fig. 2, the maturity of aircraft development is divided into N levels, and the relationship between different maturities in the different hierarchy is illustrated. Through maturity evaluation from bottom to top and quantitative maturity indicators which can decide the operation hierarchy situation, we can grasp the overall completion situation of the aircraft development and change the plan of aircraft development based on the actual evaluation results.

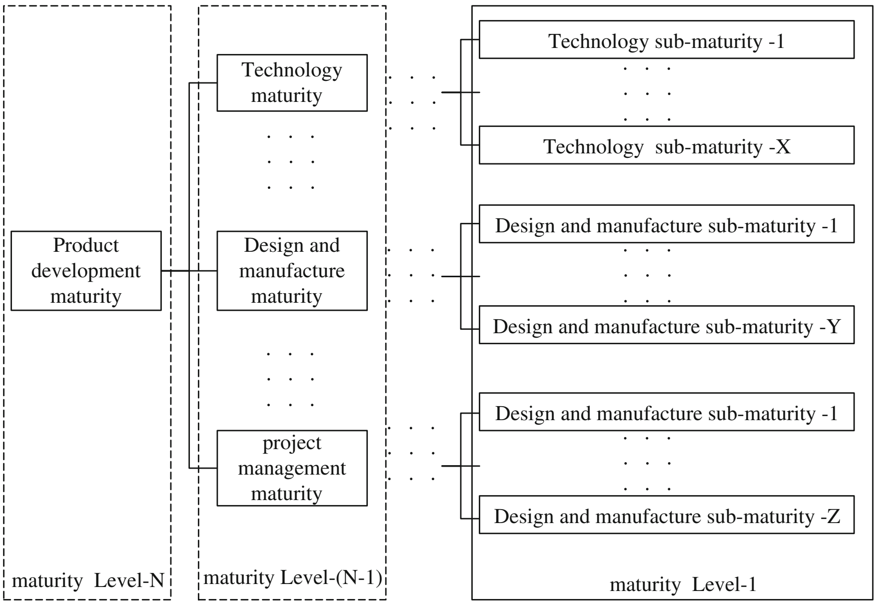

Fig. 2 Multilevel maturity schematic of product development

3 Maturity Evaluation

Maturity Evaluation is an integral part of that maturity applied in the business process of aircraft development. We can determine the level of maturity and whether or not carry out the next step only through the maturity evaluation.

3.1 Multilevel Maturity Evaluation

In the aircraft collaborative development process, rigorous maturity evaluation and evolution control are used to manage the evolution of maturity to achieve the objectives of reducing late engineering changes and improving the quality of aircraft. Many factors are involved in the multilevel maturity evaluation, and the extent of each factor is different. Therefore, there is a certain ambiguity in multilevel maturity evaluation. Fuzzy comprehensive evaluation may be a well reflection of the overall characteristics and the general trend in the aircraft development process [11].

3.1.1 Single-Level Fuzzy Evaluation

The factors set is $U = \{x_1, x_2, \ldots, x_i, \ldots, x_n\}$, and the evaluation set is $V = \{y_1, y_2, \ldots y_j, \ldots, y_m\}$.

1. Single factor evaluation
   The single factor $x_i (i = 1, 2, \ldots, n)$ in the factors set U is evaluated firstly, and the membership r_{ij} of corresponding evaluation set $y_j (j = 1, 2, \ldots, m)$ can be obtained, all the membership r_{ij} constitutes an evaluation matrix R.

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{bmatrix} \quad (1)$$

2. Determining the weights
   The weight of each factors in the multi-factor evaluation is different, so the weights set of factors should be introduced: $A = \{\alpha_1, \alpha_2, \ldots, \alpha_n\}$, where $(0 \le \alpha_i \le 1)$. A is defined as the weights set of factors and α_i is defined as the weight coefficient of factor x_i.
3. Comprehensive evaluation
   When the weights set A and the evaluation matrix R are known, $B = AR = (b_1, b_2, \ldots, b_m)$ is defined as the level fuzzy subset of evaluation set V, where $b_j (j = 1, 2, \ldots, m)$ is defined as the membership of level fuzzy subset by

comprehensive evaluation of evaluation set $y_j (j = 1, 2, \ldots, m)$. And the weighted average formula is used to calculate the result.

$$M = \sum_{j=1}^{m} b_j y_j \bigg/ \sum_{j=1}^{m} b_j \tag{2}$$

where M represents the maturity result of the objective.

3.1.2 Multilevel Fuzzy Comprehensive Evaluation

1. Factor set dividing
   The factors set $U = \{x_1, x_2, \ldots, x_i, \ldots, x_n\}$ is divided into S subsets $U_1, U_2, \ldots, U_S$, where $U_1, U_2, \ldots, U_S$ represent sub-factors of the same level. Every sub-factor is defined as $U_i = \{x_{i1}, x_{i2}, \ldots, x_{ik_i}\}$, $i = 1, 2, \ldots, S$, so there is k_i factors in U_i. Where $\sum_{i=1}^{S} k_i = n$, $\bigcup_{i=1}^{S} U_i = U$; $U_i \cap U_j = \varnothing (i \neq j)$
2. Evaluation set dividing
   Similar to the factor set dividing, the evaluation set $V = \{y_1, y_2, \ldots, y_m\}$ is divided into S subsets $V_1, V_2, \ldots, V_S$, where $V_i = \{y_{i1}, y_{i2}, \ldots, y_{ik_i}\}$, $i = 1, 2, \ldots, S$.
3. Single-level fuzzy evaluation
   The factors in $U_i = \{x_{i1}, x_{i2}, \ldots, x_{ik_i}\}$ $(i = 1, 2, \ldots, S)$ is evaluated by single-level fuzzy evaluation. A_i is defined as the weights set of factors of U_i and R_i is defined as the evaluation matrix of the k_i factors of U_i. The level fuzzy subset of evaluation set U_i can be obtained by:

$$B_i = A_i R_i = (b_{i1}, b_{i2}, \ldots, b_{im}) \tag{3}$$

4. Multilevel fuzzy evaluation
   The weight fuzzy set of factors set $U = \{U_1, U_2, \ldots, U_S\}$ is defined as $A = \{A_1, A_2, \ldots, A_S\}$, and the comprehensive evaluation matrix is $R = \{R_1, R_2, \ldots, R_S\}^T$.

$$B = \begin{bmatrix} B_1 \\ B_2 \\ \ldots \\ B_S \end{bmatrix} = \begin{bmatrix} A_1 R_1 \\ A_2 R_2 \\ \ldots \\ A_S R_S \end{bmatrix} \tag{4}$$

Through formula (4) we can get the result of multilevel fuzzy evaluation, then the multilevel maturity results can be obtained by weighted average formula (2).

3.2 Multi-Level Maturity Evaluation Process

The factors of the lowest level are evaluated firstly, then the evaluation turn up to the top level layer by layer. The process of multi-level maturity evaluation is illustrated in Fig. 3.

Step 1 The sub-factors set of the first level maturity is evaluated. Based on membership function and the advice of the experts in integrated product team, evaluation sets of each sub-factors set are calculated.
Step 2 The fuzzy relation matrix between sub-factor set and sub-evaluation set is established.
Step 3 Based on the estimate of experts, the fuzzy weight set is determined.
Step 4 The evaluation result is calculated based on the fuzzy relation matrix and fuzzy weight set.
Step 5 Based on the weighted average formula, the result is normalized.
Step 6 All factors in this level have been evaluated, otherwise, repeating step 1 to step 5.
Step 7 The upper level is evaluated by repeating step 1 to step 6.
Step 8 Until the top level is reached, otherwise, repeating step 7.
Step 9 The evaluation result of the top level is obtained, and the evaluation process is over.

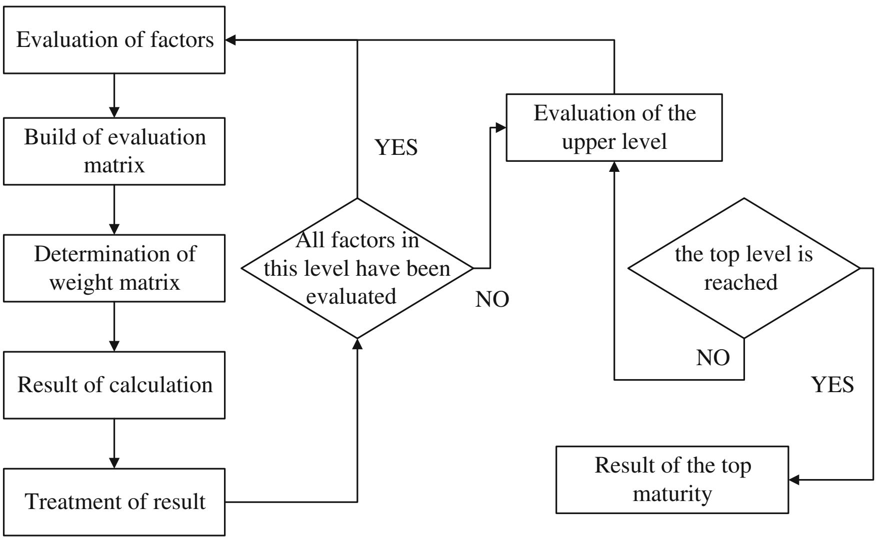

Fig. 3 Schematic of multilevel maturity evaluation process

4 Application of the Multilevel Maturity Model

In order to explain how the multilevel model is applied in aircraft development, an application example is demonstrated in the following. It is supposed that there are three maturity levels in the multilevel maturity of aircraft development, as shown in the Fig. 4. Evaluation factors are used to evaluate the maturity level-1. Maturities in level-1 are used to evaluate the maturity level-2. Maturities in level-2 are used to evaluate the maturity level-3. The evaluation set is defined as $V = \{1 \quad 0.75 \quad 0.5 \quad 0.25 \quad 0\}$. The weight of each maturity level and the membership of factors in level-1 are given in the Table 2.

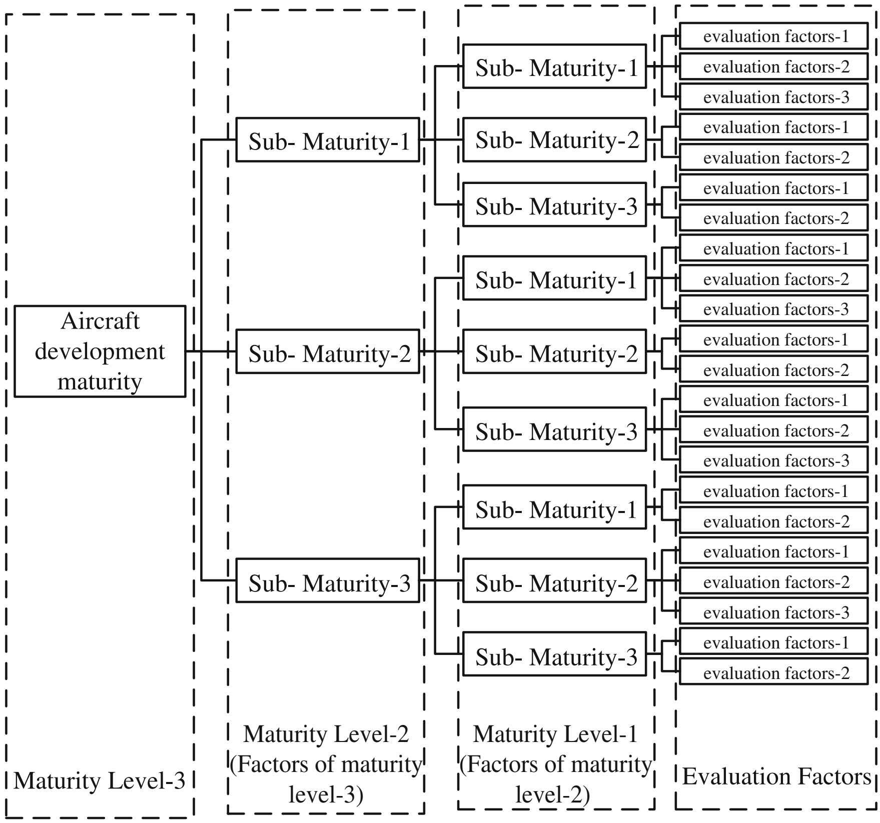

Fig. 4 Supposed multilevel maturity structure of aircraft development

Table 2 Weight of each maturity level and membership of factors in level-1

Evaluation factor	Weight	Evaluation factor	Weight	Evaluation factor	Weight	r_{ij}				
Maturity-1 of level-2	0.25	Maturity-1 of level-1	0.3	Factor-1	0.4	0.2	0.2	0.2	0.2	0.2
				Factor-2	0.3	0.1	0.1	0.3	0.2	0.3
				Factor-3	0.3	0	0	0.5	0.1	0.4
		Maturity-2 of level-1	0.4	Factor-1	0.6	0.3	0.2	0.5	0	0
				Factor-2	0.4	0	0.2	0	0.5	0.3
		Maturity-3 of level-1	0.3	Factor-1	0.7	0.2	0.5	0	0	0.3
				Factor-2	0.3	0.1	0.3	0.2	0.2	0.2
Maturity-2 of level-2	0.5	Maturity-1 of level-1	0.5	Factor-1	0.5	0.2	0.2	0.2	0.2	0.2
				Factor-2	0.1	0.1	01	0.3	0.2	0.3
				Factor-3	0.4	0	0	0.5	0.1	0.4
		Maturity-2 of level-1	0.3	Factor-1	0.6	0.3	0.2	0.5	0	0
				Factor-2	0.4	0	0.2	0	0.5	0.3
		Maturity-3 of level-1	0.2	Factor-1	0.8	0.2	0.2	0.2	0.2	0.2
				Factor-2	0.1	0.1	0.1	0.3	0.2	0.3
				Factor-3	0.1	0	0	0.5	0.1	0.4
Maturity-3 of level-2	0.25	Maturity-1 of level-1	0.1	Factor-1	0.5	0.3	0.2	0.5	0	0
				Factor-2	0.5	0	0.2	0	0.5	0.3
		Maturity-2 of level-1	0.6	Factor-1	0.4	0.2	0.2	0.2	0.2	0.2
				Factor-2	0.2	0.1	0.1	0.3	0.2	0.3
				Factor-3	0.4	0	0	0.5	0.1	0.4
		Maturity-3 of level-1	0.3	Factor-1	0.9	0.3	0.2	0.5	0	0
				Factor-2	0.1	0	0.2	0	0.5	0.3

4.1 Maturity Evaluation of Level-1

Based on the data in the Table 2, the evaluation matrix and the weight matrix of level-1 maturity are established.

$$R_{11} = \begin{bmatrix} 0.2 & 0.2 & 0.2 & 0.2 & 0.2 \\ 0.1 & 0.1 & 0.3 & 0.2 & 0.3 \\ 0 & 0 & 0.5 & 0.1 & 0.4 \end{bmatrix}$$
$$R_{12} = \begin{bmatrix} 0.3 & 0.2 & 0.5 & 0 & 0 \\ 0 & 0.2 & 0 & 0.5 & 0.3 \end{bmatrix}$$
$$R_{13} = \begin{bmatrix} 0.2 & 0.5 & 0 & 0 & 0.3 \\ 0.1 & 0.3 & 0.2 & 0.2 & 0.2 \end{bmatrix}$$

where R_{11}, R_{12} and R_{13} is the evaluation matrix of factors in sub-maturity.

$$A_{11} = [0.4 \quad 0.3 \quad 0.3] \quad A_{12} = [0.6 \quad 0.4] \quad A_{13} = [0.7 \quad 0.3]$$

where A_{11}, A_{12} and A_{13} is the weight matrix of factors in maturity.

The fuzzy comprehensive evaluation set is established through the formula $B_{ij} = A_{ij}R_{ij}$.

$$B_{11} = A_{11}R_{11} = [0.11 \quad 0.11 \quad 0.32 \quad 0.17 \quad 0.29]$$
$$B_{12} = A_{12}R_{12} = [0.18 \quad 0.2 \quad 0.3 \quad 0.2 \quad 0.12]$$
$$B_{13} = A_{13}R_{13} = [0.17 \quad 0.44 \quad 0.06 \quad 0.06 \quad 0.27]$$

where B_{11}, B_{12} and B_{13} is the fuzzy comprehensive evaluation set of level-1 maturity.

The weighted average formula is used to calculate the result that $M_{11} = 0.395, M_{12} = 0.53, M_{13} = 0.545$. As the same method applied, the results $M_{21} = 0.3975, M_{22} = 0.53, M_{23} = 0.465$, $M_{31} = 0.4875, M_{32} = 0.385, M_{33} = 0.6575$ can be obtained.

4.2 Maturity Evaluation of Level-2

The fuzzy comprehensive evaluation set of Level-2 maturity is obtained through the formula $B_i = A_iR_i = A_i\{B_{11} \quad B_{12} \quad B_{13}\}^T$. $A_1 = [0.3 \quad 0.4 \quad 0.3]$ can be established from Table 2 and $B_1 = [0.156 \quad 0.245 \quad 0.234 \quad 0.149 \quad 0.216]$ can be calculated, where B_1 is the fuzzy comprehensive evaluation set of Level-2 maturity, A_1 is the weight set of factors in Level-2 maturity. Then the weighted average formula is used to calculate the result that $M_1 = 0.494$. As the same method applied, the results $M_2 = 0.451, M_3 = 0.477$ can be obtained.

4.3 Maturity Evaluation of Level-3

The fuzzy comprehensive evaluation set of level-3 maturity is obtained through the formula $B = AR = A\{B_1 \quad B_1 \quad B_1\}^T$. $A_1 = [0.25 \quad 0.5 \quad 0.25]$ can be established from Table 2, So $B = [0.1495 \quad 0.17075 \quad 0.301 \quad 0.16025 \quad 0.2185]$ can be calculated. Then the weighted average formula is used to calculate the result that $M = 0.468$.

Through quantitative maturity results obtained ahead, the determination that the next development process could begin in advance will be made. The maturity of aircraft development is 0.468, which refers to that the completion extent of the aircraft development is 46.8 %. Compared with the arrangement of aircraft development, the adjustment of next arrangement should be made to meet the deadline.

5 Conclusion

The existing maturity models in aircraft development are applied in independent process, and the level partition and evaluation methods of the models are diverse [2–9, 11–13]. Through reasonable modular decomposition of the complex work into some relatively independent modules from the top to down hierarchically, the complexity of the work can be reduced to a certain extent. Based on the modular structure of aircraft development and maturity concept, the maturity in aircraft development is divided into N levels and the relationship between them is built, which make the management of maturity more integral and unified. Finally, the comprehensive evaluation method in fuzzy math is introduced to solve the complex problem of multilevel maturity evaluation in aircraft development process.

The multilevel maturity model proposed in this paper that including modular structure, multilevel maturity and multilevel maturity evaluation connect various maturities, and unify the level partition and evaluation methods in the aircraft development process, which offer systematic method and bring great convenience to the overall management of aircraft development process. And the result is verified to be reasonable and effective by the application example.

The multilevel maturity model is during the concept phase. It will be an important and difficult work that combining the model with the particular details of aircraft development in the next research.

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A Social Sustainability Assessment Model for Manufacturing Systems Based on Ergonomics and Fuzzy Inference System

Yang Cao, Shilong Wang, Lili Yi and Jie Zhou

Abstract Economy, environment and society are the three pillars of sustainability. Sustainability assessment is a critical tool for analyzing and improving sustainability performance of manufacturing systems. However, most previous research has either focused exclusively on the environmental dimension, or considered the three pillars together, thus being too broad in social indicators. Research gaps exist in studies on the social dimension of sustainability. This paper presents a social sustainability assessment framework from the perspective of ergonomics. The proposed assessment framework consists of three aspects, i.e., work task, work environment and human-machine interaction. A novel weighted Mamdani fuzzy inference system (FIS) is designed to obtain a social sustainability score, which is further translated into a social sustainability index.

Keywords Social sustainability assessment · Sustainable manufacturing · Ergonomics · Fuzzy inference system (FIS)

1 Introduction

Economic value, environmental and social responsibilities—the so-called triple bottom line [1]—are the three pillars of sustainability. The economic dimension of sustainability, from the perspective of a single company, is addressed as a matter of

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course in standard operating practices. On the other hand, environmentally friendly production, as forced by governmental regulations and consumer awareness, is increasingly understood and embraced by companies as a competitive advantage [2]. Although the modern concept of sustainable development is largely rooted in the 20th century's environmental concerns and resource depletion, the term sustainable manufacturing implies a great deal more than the simple act of analyzing and modifying the environmental performance of manufacturing processes and systems [3].

As a critical tool for analyzing and improving sustainability performance of manufacturing systems, sustainability assessment has been a constantly researched area. So far, relevant research has mainly fallen into two categories, environmental sustainability assessment and comprehensive sustainability assessment. Research of the first category [4–6], which has a large overlap with green manufacturing [7], focuses on the environmental impacts of gas emissions, pollutant discharge, energy and material consumption, etc. Literature of the second category such as [8–10] considers economic, environmental and social performance comprehensively. Nonetheless, social indicators in these assessment models have not received appropriate attention. In order to adequately evaluate manufacturing sustainability, more research is needed to deal with the social dimension.

2 Ergonomics-Based Social Sustainability Assessment Framework

Ergonomics, also known as human factors, plays a fundamental role in sustainability [11], and its direct positive workplace effects include injury reduction, productivity increase, quality improvement, better workforce stability and moral gains [12]. The assessment framework proposed in this paper complies with ISO 6385 [13, 14], the Ergonomic Principles in the Design of Work Systems. As shown in Fig. 1, a manufacturing system is comprised of operators, machines and the work environment. Health and well-being of operators are mainly connected with three aspects, namely work task, work environment and human-machine interaction. In the rest of this section, indicators of these three aspects are identified (see Fig. 2).

2.1 Work Task (T)

Indicators of work task measure the intensity, duration and quality of operators' work activities. A socially sustainable manufacturing system should on the one hand achieve production goals, while on the other hand be compatible with the needs, abilities and limitations of human beings. Typically, attention shall be paid to the following indicators:

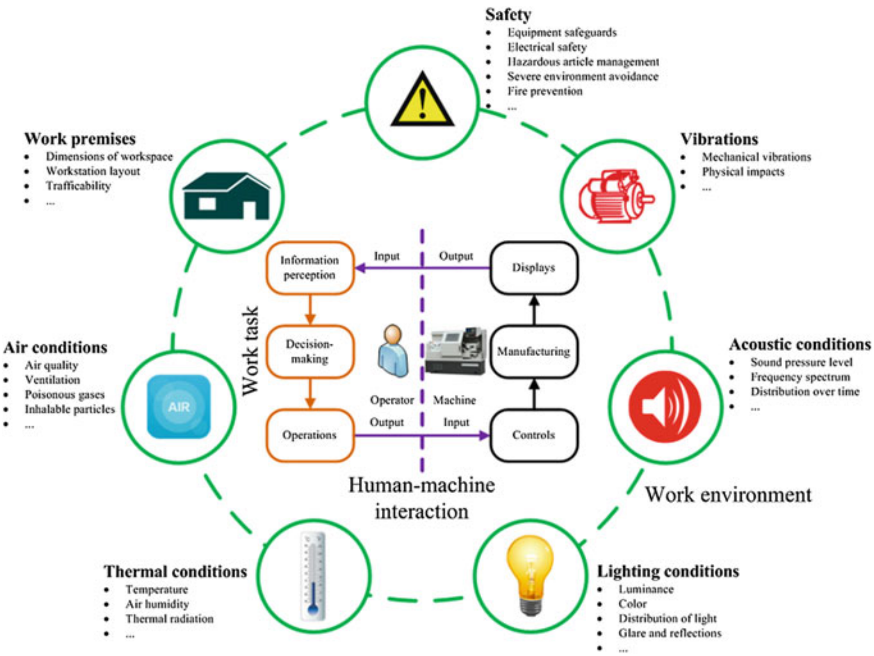

Fig. 1 The ergonomics-based social sustainability assessment framework

- **Work load (T_1)**: avoid overload as well as underload, which may lead to unnecessary or excessive strain, fatigue or errors.
- **Work time (T_2)**: work time should be compromised between production needs and human endurance; overlong work time may cause fatigue and errors.
- **Task diversity (T_3)**: repetitiveness will not only lead to sensations of satiation and boredom, but also to unbalanced work strain and thus to physical disorders.
- **Degree of autonomy (T_4)**: operators should be provided with an appropriate degree of autonomy in deciding task priority, pace and procedure.
- **Feeling of enrichment (T_5)**: significance of the work task should be identifiable, and also be understood by the operators involved.
- **Social contacts (T_6)**: appropriate opportunities for social and functional contacts are needed to maintain social entity.
- **Breaks (T_7)**: adequate breaks, organized or non-organized, need to be provided.

2.2 Work Environment (E)

In this paper, assessment of work environment mainly concerns physical factors surrounding operators. As well as ensuring that environmental conditions remain

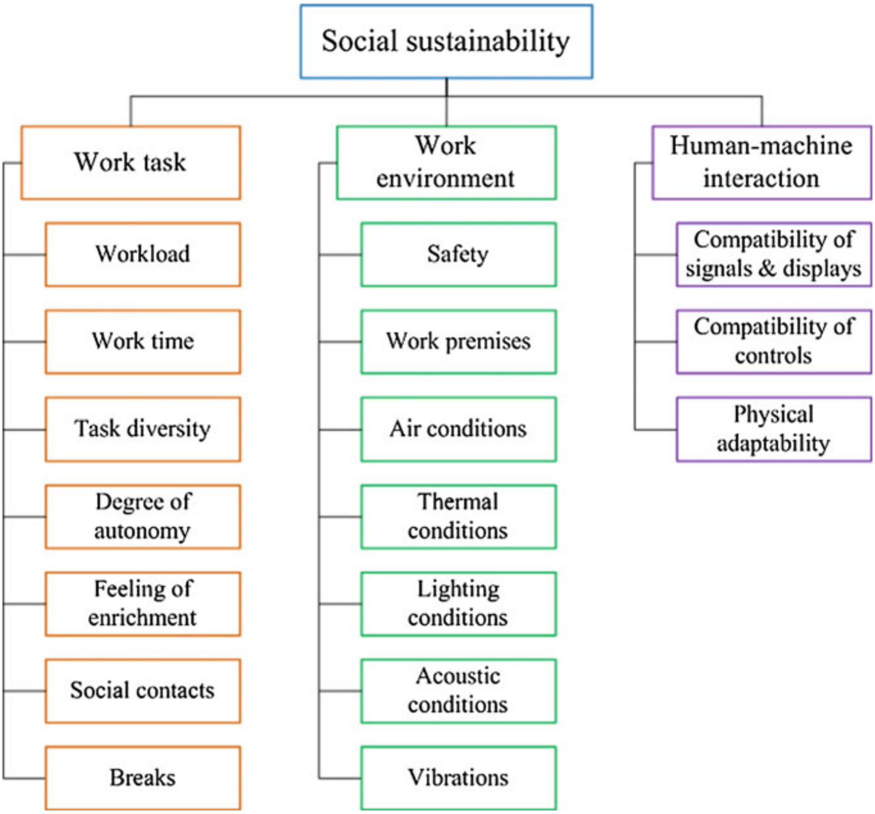

Fig. 2 The proposed indicators for the social sustainability assessment

within the recognized limits for the maintenance of health and well-being, attention should also be given to the extent to which the design of the environment can influence safe and efficient task performance. Depending on the manufacturing system, it is necessary to pay attention in particular to the following points:

- **Safety (E_1)**: safety is a vital factor in work environment, which includes equipment safeguards, electrical safety, hazardous article management, severe environment avoidance and fire prevention, etc.
- **Work premises (E_2)**: dimensions of the work premises shall be adequate, workstation layout shall be convenient, and passageways shall be enough for work-related traffic.
- **Air conditions (E_3)**: air conditions shall be adjusted with regard to factors like air quality, ventilation, poisonous gases and inhalable particles control.
- **Thermal conditions (E_4)**: thermal conditions shall be adjusted with regard to factors like temperature, air humidity and thermal radiation.

- **Lighting conditions (E_5)**: luminance, color and distribution of light shall be appropriate to provide optimal visual perception for the required activities, while glare and undesirable reflections shall be avoided.
- **Acoustic conditions (E_6)**: long exposure to intense noise may cause annoying feelings and acoustical health problems. The sound pressure level, frequency spectrum and distribution over time need to be controlled, so as to ensure perception of acoustic signals and speech intelligibility.
- **Vibrations (E_7)**: undesirable mechanical vibrations and physical impacts shall be controlled.

2.3 Human-Machine Interaction (I)

The majority of manufacturing activities involves human-machine interactions. Hence, the fitness between human and machine has great impacts on the overall system performance. Generally, the following indicators should be taken into account:

- **Compatibility of signals and displays (I_1)**: signals and displays shall be selected, designed and laid out in a manner compatible with the characteristics of human perception.
- **Compatibility of controls (I_2)**: controls shall be selected, designed and laid out in a manner compatible with the characteristics of human body.
- **Physical adaptability (I_3)**: the design of equipment shall take into account constraints imposed by body dimensions, body posture, body movement and muscular strength.

3 FIS-Based Social Sustainability Assessment Model

3.1 The Weighted Mamdani FIS

A Mamdani FIS is composed of the membership functions of inputs, fuzzy linguistic rules, and output membership functions. Fuzzy rules are a collection of linguistic statements that describe how the FIS should make a decision regarding classifying an input or controlling an output. They are written in the following form:

$$R_i\text{: If } X_1 \text{ is } A_{i1} \text{ and} \ldots \text{and } X_n \text{ is } A_{in} \text{ then } Y \text{ is } B_i.\ (i = 1, 2, \ldots, k)$$

where k is the number of rules, $X_i(i = 1, 2, \ldots, n)$ are the inputs or antecedent variables, Y is the output or consequent variable. A_{ij} and B_{ij} are linguistic terms that are defined by membership functions $A_{ij}(X_j)$ and $B_i(Y)$, respectively.

The calculation procedure of a Mamdani FIS can be given as follows [15]:

1. Compute the degree of fulfilment (α_i) of the inputs for each rule (i) by considering the degree of membership (μ):

$$\alpha_i = \mu_{A_{i1}}(X_1) \wedge \mu_{A_{i2}}(X_2) \wedge \cdots \wedge \mu_{A_{in}}(X_n) \tag{1}$$

   where $\mu_{A_{ij}}(X_j)$ represents the degree of membership that X_j belongs to A_{ij}.
2. For each rule, derive the output fuzzy set B_i^* using the minimum *t-norm*:

$$\mu_{B_i^*}(Y) = \alpha_i \wedge \mu_{B_i}(Y) \tag{2}$$

3. Aggregate the output fuzzy sets by taking the union:

$$\mu_{B^*} = \bigvee_{i=1,2,\ldots,k} \left[\mu_{B_i^*}(Y)\right] \tag{3}$$

   In a discrete domain, Formula (1) is simplified to:

$$\alpha_i = \min\left[\mu_{A_{i1}}(X_1), \mu_{A_{i2}}(X_2), \ldots .\mu_{A_{in}}(X_n)\right] \tag{4}$$

As it shows, the degree of fulfilment for each rule is calculated by taking the minimum of the degrees of membership of all the inputs. In a weighted Mamdani FIS, however, all the degrees of membership are combined, by multiplying a weight coefficient, to obtain the degree of fulfilment for each rule, i.e., modify Formula (4) to (5):

$$\alpha_i = \omega_1 \cdot \mu_{A_{i1}}(X_1) + \omega_2 \cdot \mu_{A_{i2}}(X_2) + \cdots + \omega_n \cdot \mu_{A_{in}}(X_n) \tag{5}$$

where $\sum_{i=1}^{n} \omega_i = 1$, and ω_i indicates the weight coefficient attached to input X_i. In practice, an easy approach to determine the weight coefficients is statistical average method, namely using the mean value of the weights set by a panel of experts.

3.2 *The First Stage Assessment*

The proposed FIS-based social sustainability assessment model for manufacturing systems is shown in Fig. 3. The assessment process is divided into two stages. In the first stage, three linguistic variables 'poor', 'fair' and 'good' are used for original indicator evaluation. For each indicator, its degrees of membership to these three linguistic variables are denoted by a fuzzy set $X = (x_1, x_2, x_3)$, in which x_1, x_2 and x_3 correspond to 'poor', 'fair' and 'good', respectively. The original fuzzy set can be obtained by an "experts combined with operators" survey method. The fuzzy rule base in the first stage is set as suggested [10] (listed in Table 1).

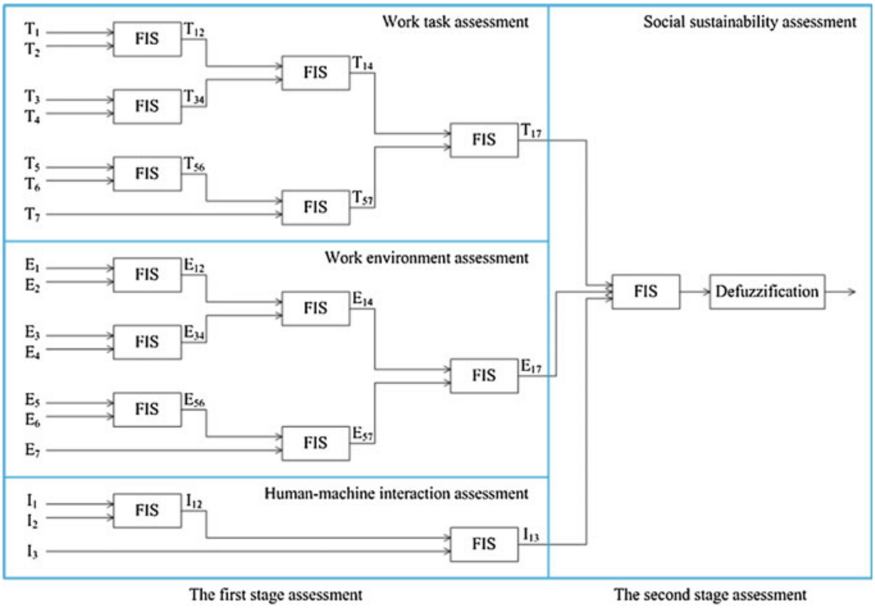

Fig. 3 The proposed social sustainability assessment model

Table 1 Fuzzy rule base for the first stage

Input1	Input2	Poor	Fair	Good
Poor		Poor	Poor	Fair
Fair		Poor	Fair	Fair
Good		Fair	Fair	Good

3.3 *The Second Stage Assessment*

At the end of the first stage, three fuzzy sets $T_{17} = (t_{17,1}, t_{17,2}, t_{17,3}), E_{17} = (e_{17,1}, e_{17,2}, e_{17,3})$ and $I_{13} = (i_{13,1}, i_{13,2}, i_{13,3})$ can be expected, which give an overall evaluation for the work task, work environment and human-machine interaction, respectively. Hereafter, a three-input Mamadani FIS is adopted in the second stage to calculate the final social sustainability score. The three-input Mamdani FIS has the same fuzzy implication relationship and inference methods with the two-input type, but different linguistic rules (listed in Table 2). To reach an accurate score, five linguistic variables are used as output fuzzy terms: E, D, C, B and A, in an ascending order. Their membership functions are given in Fig. 4.

Then the final output fuzzy set $\mu = (\mu_E, \mu_D, \mu_C, \mu_B, \mu_A)$ is obtained, in which the components from left to right indicate the degrees of membership that the evaluation belong to levels E, D, C, B and A, respectively. Defuzzification operations are needed to reach a crisp score value. The average of centers (AOC) method is

Table 2 Fuzzy rule base for the second stage

Input1	Input2	Input3	Output	Input1	Input2	Input3	Output
Poor	Poor	Poor	E	Fair	Fair	Good	C
Poor	Poor	Fair	E	Fair	Good	Poor	D
Poor	Poor	Good	D	Fair	Good	Fair	C
Poor	Fair	Poor	E	Fair	Good	Good	B
Poor	Fair	Fair	D	Good	Poor	Poor	D
Poor	Fair	Good	D	Good	Poor	Fair	D
Poor	Good	Poor	D	Good	Poor	Good	C
Poor	Good	Fair	D	Good	Fair	Poor	D
Poor	Good	Good	C	Good	Fair	Fair	C
Fair	Poor	Poor	E	Good	Fair	Good	B
Fair	Poor	Fair	D	Good	Good	Poor	C
Fair	Poor	Good	D	Good	Good	Fair	B
Fair	Fair	Poor	D	Good	Good	Good	A
Fair	Fair	Fair	D				

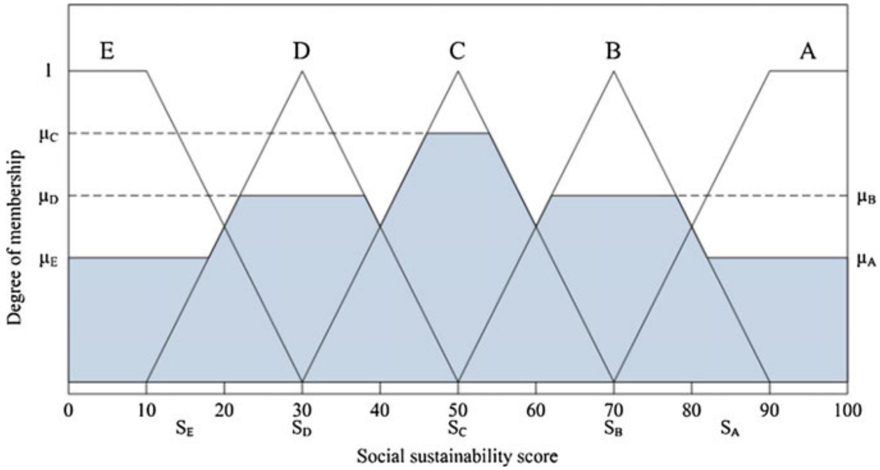

Fig. 4 Membership functions in the second stage and the AOC defuzzification method

selected for defuzzification, whose calculation procedure is given in Formula (6) and illustrated in Fig. 4.

$$S = \frac{S_E \cdot \mu_E + S_D \cdot \mu_D + S_C \cdot \mu_C + S_B \cdot \mu_B + S_A \cdot \mu_A}{\mu_E + \mu_D + \mu_C + \mu_B + \mu_A} \quad (6)$$

where $S_E = 15$, $S_D = 30$, $S_C = 50$, $S_B = 70$ and $S_A = 85$. S is the social sustainability score, which is further translated into a more intuitive social sustainability index:

$$I = (S - S_{\min})/(S_{\max} - S_{\min}) \tag{7}$$

where I is the social sustainability index (the scale is 0 to 1), $S_{\min}$ and $S_{\max}$ denote the maximum and minimum possible social sustainability scores, respectively.

4 Conclusions

Unlike most previous work, this paper constructs a social sustainability assessment framework for manufacturing systems from the angle of ergonomics, which directly relates to human well-being and overall system performance. Assessment indicators, in accordance with the ergonomic principles provided in ISO 6385, offer a comprehensive evaluation of the ergonomic performance of a manufacturing system. A novel weighted Mamdani FIS is then designed for the assessment model. Compared with the traditional Mamdani FIS, it can utilize more input information and reflect the relative importance of different indicators.

Acknowledgements The research presented in this paper is supported by National Key Technology Research and Development Program of the Ministry of Science and Technology of China (no. 2015BAF02B02).

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Cloud Manufacturing Service-Oriented Platform for Group Enterprises

Ling Kang, Shilong Wang and Changsong Li

Abstract The purpose of this paper is to put forward a new cloud manufacturing (CMfg) service-oriented platform for Group Enterprises (GEs), providing high-efficiency and intelligent manufacturing services by organizing isolated manufacturing resources in a collaborative manner. Relevant research has rarely focused on a general services platform and application model oriented at GEs. Incorporating the thought of cellular manufacturing, a new service-oriented platform for GEs is proposed in this paper. The core running process is critical for the development of the serviced-oriented platform. Finally, simulation by using Hypertext Preprocessor (PHP) and MySQL proved the feasibility and practicability of the platform for GEs.

Keywords Cloud manufacturing (CMfg) · Group enterprises (GEs) · Cellular manufacturing

1 Introduction

Inspired by the need of moving from production-oriented manufacturing to service-oriented manufacturing, a new manufacturing paradigm called cloud manufacturing (CMfg), was therefore proposed in 2010 by Li et al. [1]. Manufacturing services in CMfg cover the whole product life cycle and are scheduled intelligently to finish resource demanders' requirements [2]. CMfg performs large-scale collaborative manufacturing under the support of Application

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Service Provider (ASP), cloud computing technology, Internet of Things, semantic web technology, knowledge-based services, etc. [3]. Compared with Grid Manufacturing, CMfg for GEs not only can handle a mechanical part task, but also enhance the utilization of certain idle machine tools (e.g., costly high-precision machine tools, non-traditional machining tools or some necessitous ordinary machine tools) for various tasks.

The biggest challenge to China's economic reform is to keep Chinese state-owned enterprises (SOEs), Small and medium-sized enterprises (SMEs), and Group Enterprises (GEs) profitable and solvent [4–6]. GEs are an economic union of more than one legal entity, whose headquarters and subsidiaries are closely linked through equity, capital, technology, and other ties. What faced by the cross-regional GEs is not only the growth in business scale, but also the growth in management content and management scopes.

In CMfg, distributed resources are encapsulated into cloud services and managed in a centralized way. Cloud users can request resources or services ranging from product design, manufacturing, testing, management and all other stages of a product life cycle according to their requirements.

2 The CMfg Service-Oriented Platform for GEs

2.1 The Framework of CMfg Service-Oriented Platform

A framework of CMfg service-oriented platform for GEs is established in Fig. 1. In the process of collaborative planning, task assignment and execution tracing and some other management capabilities, the CMfg platform classifies each processing plant according to the type of processing parts of GEs, in order to form a relatively independent manufacturing unit. People who work in the unit exercise the necessary decision-making powers of production preparation and control, with the help of computers, and are responsible for the implementation and monitoring of the decision-making program. All of this will form a relatively independent and regional autonomous closed-loop production system, which is called Manufacturing Cellular [7–9]. Every manufacturing unit is a manufacturing work cell (MWc). The platform constitutes of three roles, which include Resource Provider, Resource Demander and System Agent. Each MWc, on behalf of a class of independent units of machining parts, makes up the manufacturing sector of GEs together. The processing progress and processing quality of resources must be closely integrated with the company's core manufacturing processes in order to ensure the completion of overall production scheduling and high quality. At the same time, taking into account the close integration of core business process management of the enterprises, the platform integrates the ERP system to achieve the interoperability of the CMfg platform and manage internal business data.

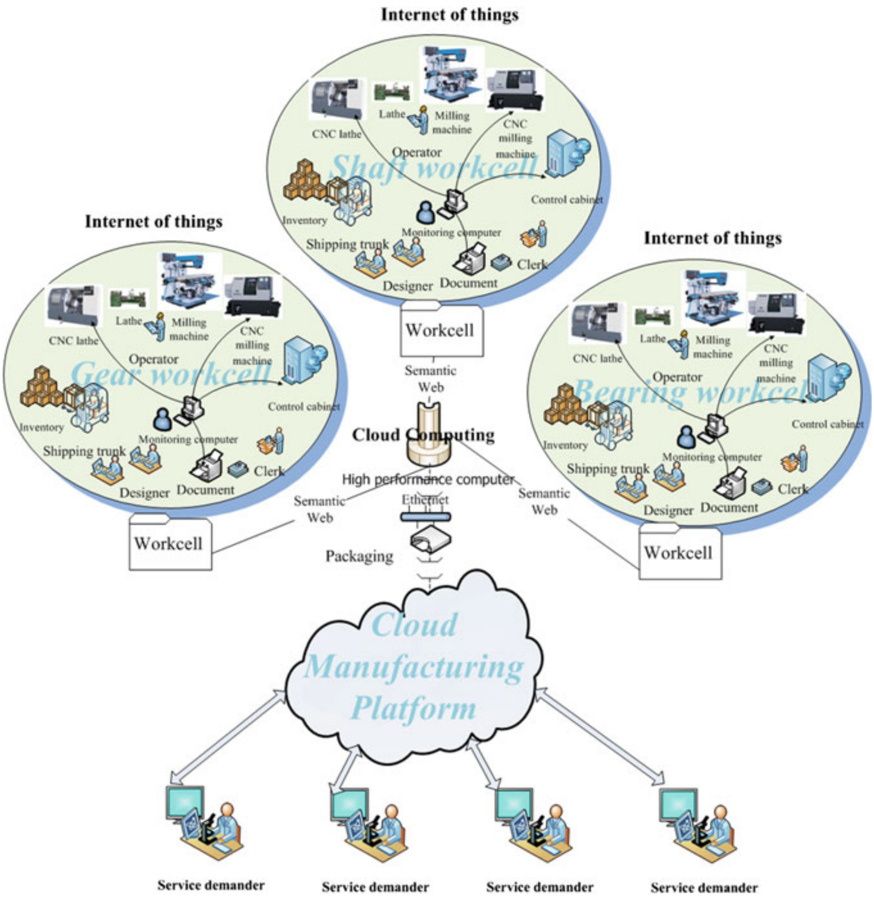

Fig. 1 A framework of CMfg service-oriented platform for GEs

2.2 *The Composition Module of the Platform*

The establishment of CMfg service-oriented platform for GEs will be an important means to enable GEs to fully utilize and share manufacturing resources. The composition module of the platform can be summarized as follows.

1. Database establishment. Using group technology (GT), combined with part classification and coding system to code and store parts and machining process features (such as the outer cylinder, straight hole), according to their similarity and heterogeneity. This contributes to the establishment of public database. For example, Resource Database (*such as machine tools, work holding measuring tools, personnel data*); Conditions Database, which reflects a variety of data for the production activities in the work cell including the processing tasks acquired

from the factory; Process Database, which includes various data related to the process scale and CNC motif of the parts processing; Part Database (*original drawings data of the parts, raw material, process collaboration, storage location,* etc.).

2. Resource description and packaging. Use semantic web technologies to describe a variety of manufacturing resources, integrate and manage manufacturing resource information centrally in the information integration framework of CMfg platform [10]. Use Internet of Things technologies and embedded technologies to achieve virtualization and embedded access of manufacturing resources in the work cell. At last, the database should be packaged to the CMfg platform and combined with ERP technology of enterprises.
3. The publishing and matching of resources. Use high-performance computers and cloud computing technologies to achieve the search and matching of manufacturing resources. A service matching and optimization method should be proposed to measure the matching degree between cloud service resources and demands.
4. System management. Everyone in the work cell should have the ability to formulate production plan, determine the policy and analyze complex systems to a certain extent, have continuous needs of learning new production technologies. The management of the CMfg system becomes very flexible without allocating too much managers.

3 The CMfg Service-Oriented Platform for GEs in Machining Process

3.1 The Core Running Process of the Platform

CMfg platform in machining process includes three roles: System Agent, Resource Provider and Task Demander. System Agent serves as an entity throughout the entire process.

From the perspective of a Resource Provider, the running process of the platform in machining process is shown in Fig. 2. The core running processes of the platform are shown as follows.

1. Resource Provider submits basic information of resources (including provider name, provider address, equipment type, machining feature, maximum precision level, maximum surface roughness, maximum weight, etc.) through the platform;
2. System Agent carries out the first round match of basic information on the resources and tasks. If the basic information is consistent with each other, the "Resource-Task" basic information sheet will be formed; if not, Resource Provider will need to modify the basic information for re-match;

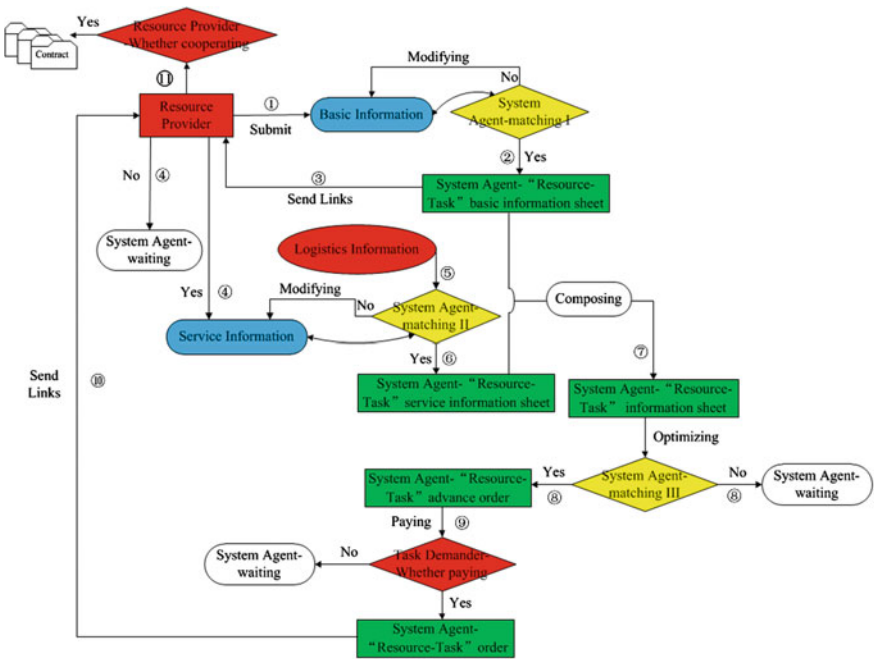

Fig. 2 The running process of the platform from the perspective a resource provider

3. System Agent will send the "Resource-Task" basic information sheet in the form of link via e-mail or text message back to the Resource Provider;
4. Resource Provider decides whether to participate in cooperation based on the linked page. If yes, it will submit service information (including price, trading date, material, etc.) of resources to the platform; if not, it will return to the waiting state;
5. System Agent automatically detects logistics information;
6. System Agent carries out the second round match of service information on the resources and tasks. If the service information is consistent with each other, the "Resource-Task" service information sheet will be formed; if not, Resource Provider will need to modify the service information for re-match;
7. System Agent composes the "Resource-Task" basic information sheet and "Resource-Task" service information sheet into "Resource-Task" information sheet;
8. System Agent carries out the third round match of "Resource-Task" information sheet based on optimization model released by Task Demander. If it is satisfied, the "Resource-Task" advance order will be formed; if not, the Task Demander will need to modify the optimization model for re-match;
9. Task Demander decides whether to pay for it after checking "Resource-Task" advance order. If the payment is completed, the "Resource-Task" order will be formed; if not, it will return to the waiting state;

10. System Agent will send the "Resource-Task" order in the form of link via e-mail or text message back to the Resource Provider for its view;
11. Resource Provider views order details. If there is a willingness to cooperate, a contract will be formed, then the service begins; if abandoned, it will return to the waiting state.

From the perspective of a Task Demander, the running process of the platform in machining process is shown in Fig. 3. The core running processes of the platform are shown as follows.

1. Task Demander submits basic information of tasks (including demander name, demander address, equipment type, machining feature, machining size, precision level, surface roughness, weight, number, etc.), service information of tasks (including price, trading date, etc.), optimization model of tasks (including time, cost, quality, credit, etc.) through the platform;
2. System Agent carries out the first round match of basic information on the resources and tasks. If the basic information is consistent with each other, the "Resource-Task" basic information sheet will be formed; if not, Task Demander will need to modify the basic information for re-match;

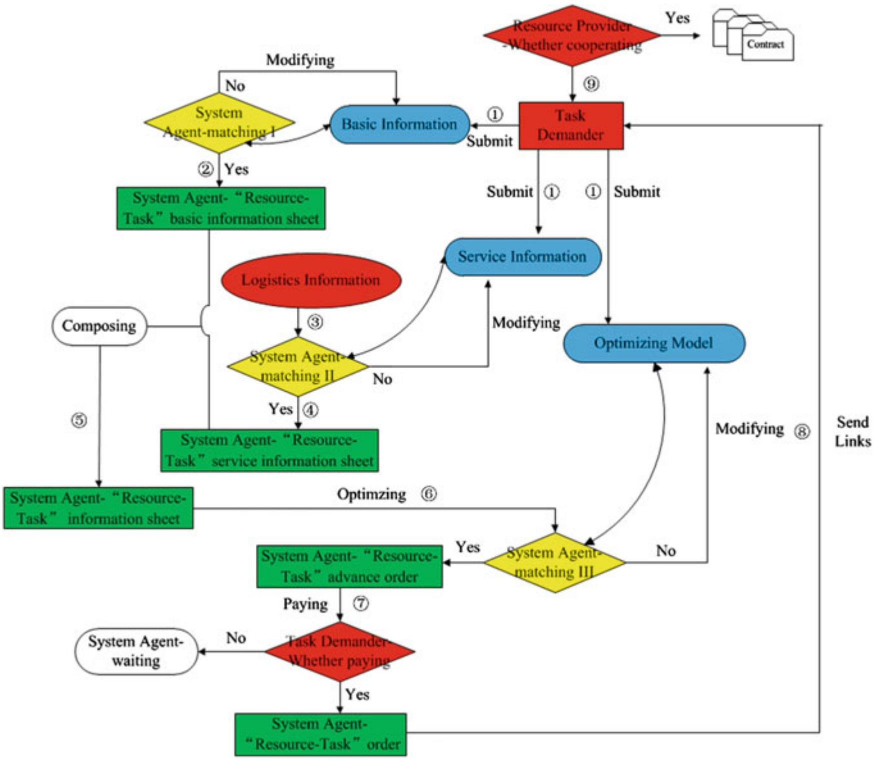

Fig. 3 The running process of the platform from the perspective of a task demander

3. System Agent automatically detects logistics information;
4. System Agent carries out the second round match of service information on the resources and tasks. If the service information is consistent with each other, the "Resource-Task" service information sheet will be formed; if not, Task Demander will need to modify the service information for re-match;
5. System Agent composes the "Resource-Task" basic information sheet and "Resource-Task" service information sheet into "Resource-Task" information sheet;
6. System Agent carries out the third round match of "Resource-Task" information sheet based on optimization model released by Task Demander. If satisfied, the "Resource-Task" advance order will be formed; if not, the Task Demander will need to modify the optimization model for re-match;
7. Task Demander decides whether to pay for it after checking "Resource-Task" advance order. If the payment is completed, the "Resource-Task" order will be formed; if not, it will return to the waiting state;
8. System Agent will send the "Resource-Task" order in the form of link via e-mail or text message back to the Task Demander for its view;
9. Task Demander views order details. If there is a willingness to cooperate, a contract will be formed, then the service begins; if abandoned, it will return to the waiting state.

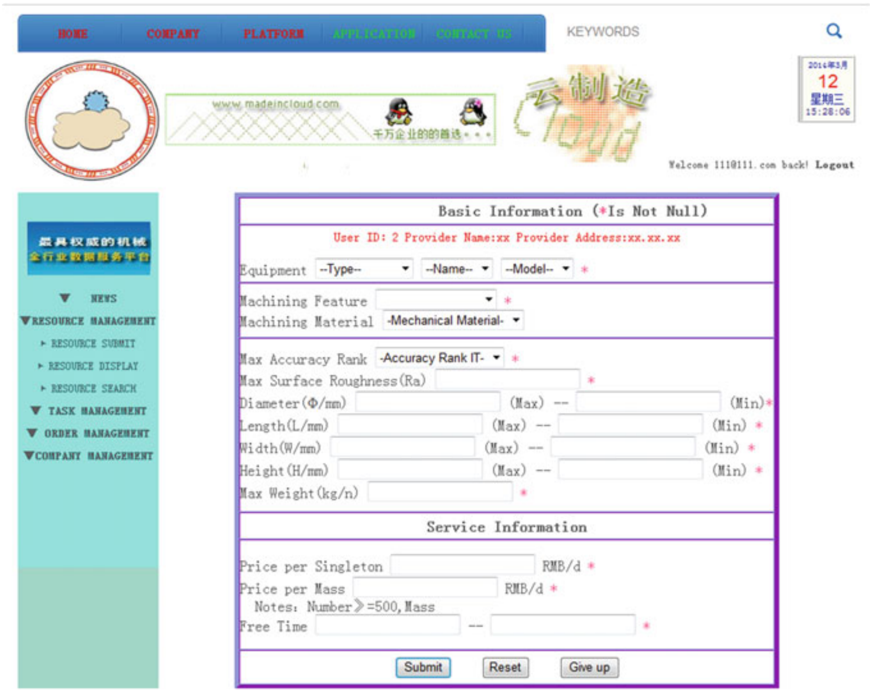

Fig. 4 The resource submit interface

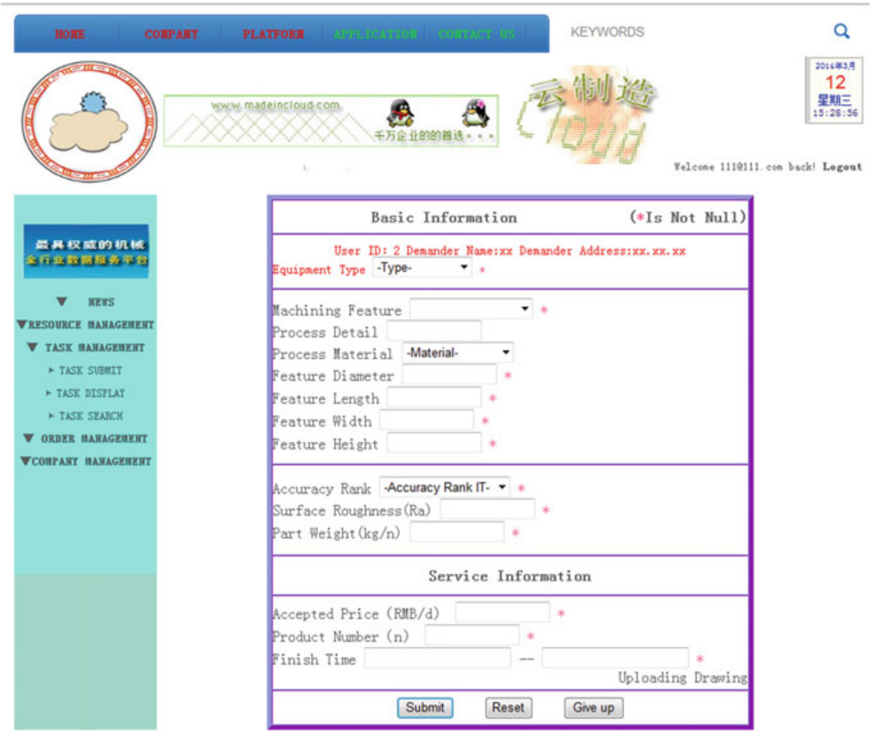

Fig. 5 The task submit interface

3.2 *Simulation of the Running Process of the Platform*

PHP and MYSQL are used to simulate the running process of the platform in machining process. Based on the resource information model and task information model in the field of machinery manufacturing established in previous work [11], the platform has developed a few small management systems, such as resource management, task management, order management, corporate management. These systems are able to simulate the formation of the Resource-Task orders. It not only achieves the publishing and sharing of resources and tasks, but also achieves a smart matching and optimization of resources and tasks.

Resource Provider submits basic information and service information of resources (shown in Fig. 4). Task Demander submits basic information and service information of tasks through the platform (shown in Fig. 5). As it is a simulation of the platform, we have put the basic information and service information of tasks in the same page. The matching of resource and task is shown in Fig. 6.

Fig. 6 The matching of resource and task

4 Conclusions

In this paper, we establish a framework of CMfg service-oriented platform aimed at GEs. The running process of the CMfg platform is proposed. We have simulated the running process of the platform using PHP and MYSQL, which has proved the feasibility of the proposed running process of the platform. CMfg draws a blueprint for the future manufacturing industry and reflects a novel idea of service-oriented manufacturing. In our future work, we will improve the development of the service-oriented platform, and focus on the intelligent embedded intervention of hard manufacturing resources to achieve the specific application of CMfg in GEs.

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Mathematical Model of Multi-source Energy Flows for CNC Worm Wheel Grinding Machine Tools

Liu Pengxiang, Li Guolong and Cao Huajun

Abstract The energy model of CNC worm wheel grinding machine tools is an important basis of the analysis of energy consumption characteristics and energy optimization. In this paper, the multi-source energy flows are divided into four parts that are main driving system, feeding system, grinding wheel dressing system and auxiliary system for the structural features of CNC worm wheel grinding machine tools. The mathematical model of multi-source energy flows is established based on the analysis of energy flow balance equation of the four parts. The energy flow models play an important supporting role in the evaluation of energy utilization effect and factors affecting energy consumption, prediction of energy consumption and optimization of energy saving.

Keywords CNC worm wheel grinding machine tools · Energy consumption · Energy flows model · Efficiency · Prediction

1 Introduction

Gears, as the basic components of mechanical equipment, are widely used in the automotive, aviation, ships, machine tools, agricultural machinery, mining, metallurgy and other fields. As the "Made in China 2025" plan to strengthen the quality of brand and full implementation of green manufacturing are proposed, the requirements of improving precision and energy efficiency in processing gear are also becoming extremely urgent. The worm wheel grinding machine tools as one of gear precision machine tools is suitable for finishing high-precision gears. With the high reliability, excellent performance, and high production efficiency, it is widely used in mass production of grinding spur and helical gears. The worm wheel grinding machine tools is a complex machine tools. On the one hand, it has some

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common energy characteristics with general machine tools, including large energy consumption, low energy efficiency, and high emissions, and on the other hand it has complex mechanical structures with a total of 10 axes, including six CNC axes, which can achieve a six-axis four linkage. Besides, there are different kinds of energy systems known as a typical mechatronic products. Therefore, the study of energy consumption characteristics and energy efficiency technology upgrade of CNC worm wheel grinding machine tools is the inevitable requirement of full implementation of green technology manufacturing.

Many domestic and foreign institutions and scholars have conducted extensive studies around energy consumption, energy efficiency and the corresponding monitoring method of machine tools and workshops. Draganescu et al. [1] established a mathematical model of the machine energy efficiency and process parameters to predict the machining energy using the method of experimental analysis. Dietmair and Verl [2] found an energy consumption model of machining system to study the possibility of any given machining systems for energy consumption. According to the assume that the output power is a function related to the spindle speed and the input power, Murari [3] used the approach of multiple linear regression analysis to deter-mine their quantitative relationship and proposed a model of power loss and energy efficiency. Liu et al. [4] systematically discussed the theory and technology of green manufacturing in terms of the introduction of green manufacturing, theoretical system, key technology, related environmental management system standards and regulations. Li [5] studied the design of high-speed dry-cutting gear hobbing for green manufacturing and dry-cutting technology. Jinliang and Fei [6] established power balance equation about the CNC machine tool's main driving system driven by variable voltage variable frequency. In addition, the power transition characteristics of main motor and mechanical transmission system and the energy loss on every section are analyzed. As can be seen from the present status of the machine tool industry energy research, the current study focuses on the energy consumption characteristics and energy flow models of general machine tools. However, there is a lack of CNC worm wheel grinding machine tools. Compared with ordinary machine tools, structure and energy characteristics of CNC worm wheel grinding machine tools have undergone great changes. The number of energy consumption components is increasing and the energy consumption laws is also more complicated. Moreover, the proportion of energy consumption of main driving system is reduced. CNC worm wheel grinding machine tools are bound to achieve the goal of energy saving and comply with the trend of green manufacturing development as the future direction of precision gear machining.

In this paper, the energy consumption characteristics and energy flow of CNC worm wheel grinding machine tools are conducted a systematic analysis. First, obtain the energy consumption characteristics through the analysis of processing technology and structural features. Secondly, the mathematical model of energy flow is established combined with its energy consumption characteristics. Finally, the assessment methods of energy efficiency of CNC worm wheel grinding machine tools are put forward.

2 Processing Technology and Structural Features

2.1 Processing Technology

The worm wheel grinding processing is a generating machining of continuous indexing. The worm wheel and workpiece work on the principle of crossed helical gears, as shown in Fig. 1. It has higher efficiency than other grinding method owing to the key feature of continuous indexing. It applies to large quantities of gear machining. The precision of grinding teeth is 4–5, as shown in Table 1.

At present the study of the mechanical structure and controlling technology for gear grinding processing technology is more deeply. As a result, more advanced mechanical system and control technology are applied to the grinding machine tools and improved the grinding gear processing technology. However, it also causes larger amount and more complex laws of energy consumption. The study of energy consumption characteristics of CNC worm wheel grinding machine tools will promote its improvement and development.

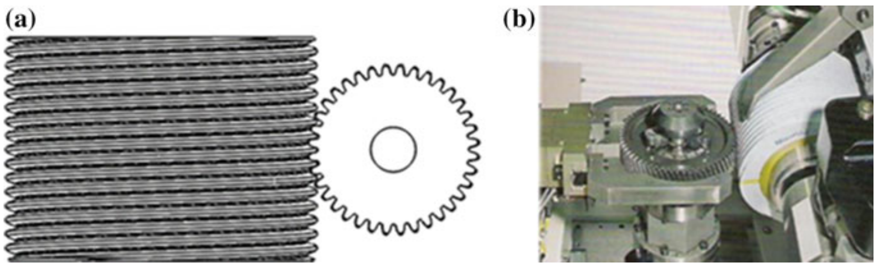

Fig. 1 Worm wheel grinding process. **a** Grinding processing principle. **b** Physical grinding process

Table 1 Machine main technical parameters of YW7232CNC

Main specifications	Technical data
The maximum diameter of the workpiece	320 mm
The maximum modulus of the workpiece	6 mm
The maximum spindle speed of the wheel (B-axis)	10,000 rpm
The highest table speed (C-axis)	1000 rpm
The rapid traverse rate of X-axis	10,000 mm/min
The rapid traverse rate of Y-axis	10,000 mm/min
The rapid traverse rate of Z-axis	8000 mm/min
The spindle power of the wheel	40 kW

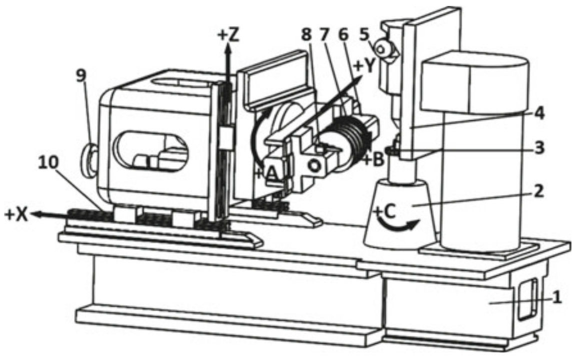

Fig. 2 The schematic diagram of CNC worm wheel grinding machine tools. *1*—machine bed, *2*—table, *3*—workpiece (gear), *4*—machine tailstock (W-axis), *5*—diamond wheel, *6*—torque motor, *7*—worm wheel, *8*—probe, *9*—ball screw, *10*—rail

2.2 Structural Features

CNC worm wheel grinding machine tools integrates mechanical, electrical, hydraulic and interdisciplinary technology, which significantly improve its processing accuracy and work efficiency. Figure 2 shows a structural schematic of the worm wheel grinding machine. There are three CNC rotating axes as follows: A-axis wheel rotary motion, B-axis wheel rotation, and C-axis table rotational movement; Three moving shafts as follows: X-axis radial feeding movement, Y-axis tangential feeding motion (or flee cutter movement), and Z-axis feeding motion. Each axis motion of machine tools is driven by independent AC servo motor, which drives the moving parts to complete the corresponding rotary or linear motion with the help of gear pairs and ball screws. Compared with conventional machine tools, its wheel spindle adopts zero-transmission technology without gear and pulley drives. It directly connects motor to the load, hence improves the accuracy of motion and reduces friction loss. It achieves generating motion involved in axis feeding motion, the differential motion, axis linkage and others. All make CNC worm wheel grinding machine tools operation more simple and humane.

3 Characteristics of Energy Consumption

Overall, the energy consumption of CNC worm wheel grinding machine tools consists of three categories-mechanical consumption, electrical loss and hydraulic consumption. Mechanical consumption is the power spending on mechanical parts from transmission system to work [7]. Electrical loss refers to the copper loss, iron loss, hysteresis loss, stray loss and others during the motor operation [8]. Hydraulic consumption is caused by volume loss and hydraulic loss of hydraulic components. In summary, the energy form of CNC worm wheel grinding machine tools covers three areas of machinery-electric-hydraulic areas and its energy law is very complex, (Fig. 3).

Energy consumption system of CNC worm wheel grinding machine tools is a dynamic process of input and output, which has three features. First, many energy consumption components and huge energy consumption. Energy consumption components of grinding machine tools include spindle motor, feed motor, inverter, servo drives, hydraulic cooling, lubrication, chip removal, flushing, lights, fans and other auxiliary system components. Take YW7232CNC worm wheel grinding machine tools as an example, the total amount has reached 15 or more, illustrated in Table 2. Second, plenty of energy flow links and complex energy flows. The generating motion is composed of wheel rotational motion, feed motion along Z-axis and work-piece rotational motion. Each motion contains respective no-load energy consumption, grinding power consumption, additional loss and the friction loss between the various transmission chains. Third, the startup process and machining process are relatively specific. The startup of grinding machine tools is usually the mode of starting-Standby-Empty- grinding. Each stage of the mode starts the fixed part of the energy consumption. Therefore, the corresponding phase transition of power is relatively stable. According to the requirements of gear processing level, the selections of processing of gear grinding change less and thus the energy consumption laws present a consistency. It is beneficial for different grinding machine tools to apply the same monitoring methods, which contributes to enhancement of the universality and practicability of monitoring system.

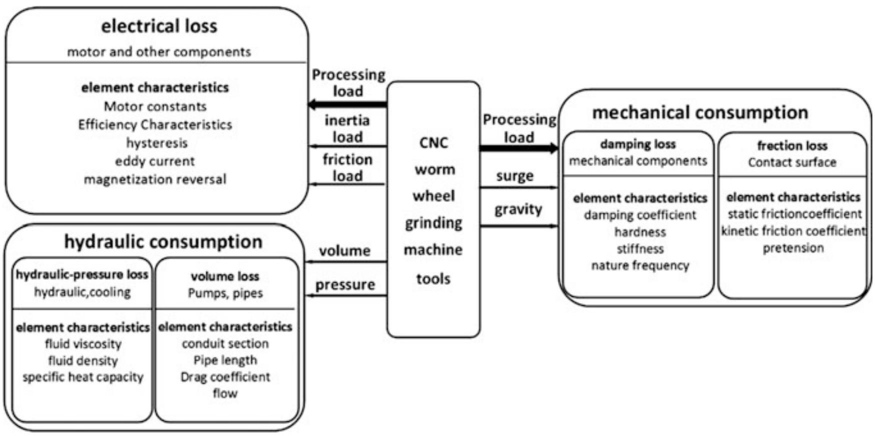

Fig. 3 Energy consumption of CNC worm wheel grinding machine tools

Table 2 Energy-consumption distribution of YW7232CNC grinding machine tools

Energy flow	Energy consumption component	Rated power/kW
X-radial feeding system	Servo motor	5.81
Y-tangential feed system	Servo motor	2.2
Z-axis feed system	Servo motor	5.81
A corner feed system	Servo motor	3.24
B main driving system	Torque motor	38.7
C table rotation system	Servo motor	67.4
Workpiece clamping system	Servo motor	2.2
Grinding wheel dressing system	Servo motor	1.88
Water cooling system	Water-cooled motor	3.3
Oil cooling system	Oil cooled motor	4.0
Hydraulic system	Hydraulic motor	7.5
Static pressure system	Hydrostatic motor	7.5
Bed flushing system	Bed flushing motor	1.3
Tank flushing system	Tank flushing motor	2.2
Oil mist separator system	Oil mist separator motor	1.05

4 The Model of Energy Flows

The conversion process of the energy from input to output can be constantly seen as an energy flow during the grinding process. It is hard to study every energy consumption component because of the characters of huge and complex energy consumption. From the perspective of CNC worm wheel grinding machine tools large system, the total energy flows are divided into four parts, namely energy flows of main driving system, feeding system, grinding wheel dressing system and auxiliary system.

$$P_M = P_S + \sum_{i}^{m} P_{x_i} + P_y + \sum_{j}^{n} P_{z_j} \tag{1}$$

where

P_M the total power input of grinding machine tools
P_S the input power of main driving system
P_{x_i} the input power of a feeding system
P_y the input power of grinding wheel dressing system
P_{z_j} the input power of an auxiliary system
m the total number of feeding systems
n the total number of auxiliary systems.

4.1 Energy Flows Modelling of Main Driving System

Electro-spindle is used in grinding machine tools as spindle driver form. The use of torque motor could integrate motor and rotating parts with zero main driving chain, which is called zero transmission. The energy consumption of main driving system comprises an inverter, a torque motor and the main driving mechanical system, as is shown in Fig. 4.

The energy consumption of inverter can be calculated from the following relationship [9]:

$$P_a = P_{a1} + P_{a2} + P_{a3} \tag{2}$$

where

P_a the energy consumption of inverter
P_{a1} the forward loss
P_{a2} the switching loss
P_{a3} the recovery loss.

The energy consumption of the wheel spindle motor is given by:

$$P_b = P_{F_e} + P_{C_u} + P_{st} + \frac{dE_m}{dt} + \frac{dE_{ne}}{dt} + P_{fs} + P_{bs} + P_1 \tag{3}$$

where

P_b the input power of main driving motor
P_{F_e}, P_{C_u} the iron loss and copper loss
P_{st} the stray loss
E_m electromagnetic loss
E_{ne} the kinetic energy loss
P_{fs} the friction loss of the rotor
P_{bs} the additional load loss
P_1 the output power of the main driving motor.

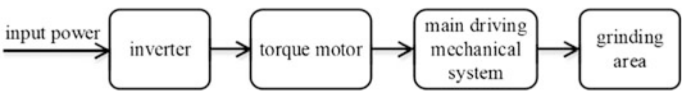

Fig. 4 The energy flow of main driving system

The energy consumption of the main driving mechanical system be written as:

$$P_c = P_m + \sum_{j}^{k} \left(P_{cf_i} + \frac{dE_{cni}}{dt} \right) \tag{4}$$

where

- P_c the energy consumption of the main driving mechanical system
- P_m the output power of the main driving mechanical system, namely grinding power
- P_{cf_i} friction loss of the transmission parts
- E_{cni} the kinetic energy loss of transmission parts
- k the total number of transmission parts.

Thus, simultaneous Eqs. (2), (3) and (4), the energy consumption of main driving system can be presented as follows:

$$P_S = P_a + P_b + P_c \tag{5}$$

4.2 Energy Flows of Feeding Systems

The energy consumption of the feeding system consists of servo drivers, servo motors and the feeding mechanical system, as shown in Fig. 5.

The energy consumption of AC servo driver can be written in the following form [10]:

$$\begin{aligned} P_e = {} & \frac{3}{\pi} \int_0^{\pi} P_{l1} \left[\sqrt{2}(\sin(\omega t) I_r), F_{sw}, \delta(\omega t,\ \mathrm{V}_{orel}) \right] d\omega t \\ & + \frac{3}{\pi} \int_0^{\pi} P_{l2} \left[\sqrt{2}(\sin(\omega t) I_r), F_{sw}, 1 - \delta(\omega t, \mathrm{V}_{orel}) \right] d\omega t \end{aligned} \tag{6}$$

where

- P_e the energy consumption of AC servo driver
- P_{l1} the switching loss of single IGBT module
- P_{l2} the conduction loss of IGBT module
- δ the duty ratio

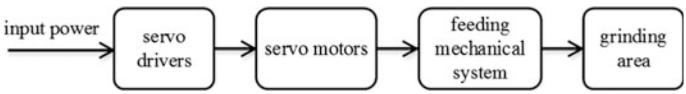

Fig. 5 The energy flow of feeding system

I_r the heat rating current
F_{sw} the nominal carrier frequency
V_{orel} the modulation.

The balance equations of servo motor power can be established:

$$P_f = P_{F_e} + P_{C_u} + P_{st} + \frac{dE_m}{dt} + \frac{dE_{ne}}{dt} + P_{fs} + P_{bs} + P_2 \quad (7)$$

where
P_f the input power of feeding motor
P_2 the output power of feeding motor.

The energy consumption of the feeding mechanical system be written as:

$$P_g = P_n + \sum_{i}^{k} \left(P_{f_i} + \frac{dE_{ni}}{dt} \right) \quad (8)$$

where
P_g the energy consumption of the feeding mechanical system
P_n the output power of the feeding mechanical system

The grinding process needs several feeding system to work together because of the requirement of mechanical linkage. Thus, the energy flows of feeding system can be expressed as:

$$P_x = \sum_{j}^{n} P_{e_j} + \sum_{j}^{n} P_{f_j} + \sum_{j}^{n} P_{g_j} \quad (9)$$

4.3 *Energy Flows of Grinding Wheel Dressing System*

Grinding wheel dressing is mainly used for trimming the profile and crest circle of the wheel. It is composed of servo driver, servo motor and the dressing mechanical system, as shown in Fig. 6.

The computational model of energy consumption of grinding wheel dressing sys-tem is similar to the feeding system as given by:

$$P_y = P_h + P_k + P_l \quad (10)$$

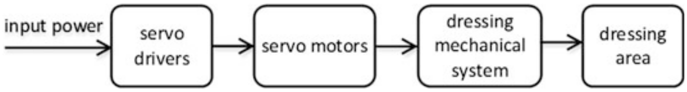

Fig. 6 The energy flow of grinding wheel dressing system

where

P_h the energy consumption of servo driver
P_k the energy consumption of servo motor
P_l the energy consumption of the dressing mechanical system.

4.4 Energy Flows of Auxiliary Systems

The auxiliary systems of CNC worm wheel grinding machine tool scan be divided into two categories. One is related to the motor, including hydraulic, cooling, lubrication, chip removal, flushing and others, and the other is opposite, including lights, fans, and computer and so on. As a result, the more energy consumption components, the more complex laws of energy consumption are, as shown in Fig. 7.

However, the energy consumption of auxiliary systems is relatively stable and less affected by the load [11], so rated power can be used to approximately obtain actual input power.

$$P_z = \sum_{i}^{m} H_i(t) P_i \tag{11}$$

where

$H_i(t)$ the activation function of auxiliary systems, $H_i(t) = 0$ represents used, $H_i(t) = 1$ represents unused.
P_i the actual input power of an auxiliary system.

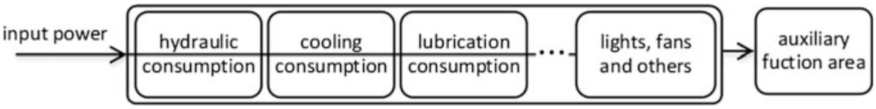

Fig. 7 Energy flows of auxiliary systems

The operation energy consumption of CNC worm wheel grinding machine tools consists of four parts, namely, the energy consumption of main driving system, feeding system, grinding wheel dressing system and auxiliary system. In summary, the mathematical model of multi-source energy flows can be written as follows:

$$E_M = E_S + E_x + E_y + E_z = \int_{T_1}^{T_2} P_M dt = \int_{T_1}^{T_2} (P_S + P_x + P_y + P_z) dt \tag{12}$$

5 Application Analysis of the Model of Energy Flows

Data supporting for different operating conditions, energy links and energy sources can be provided by monitoring the process of energy flows and counting energy consumption of each energy link. Besides, it also provides scientific basis for energy efficiency analysis, forecasting and energy optimization.

5.1 Establish the Assessment Model of Energy Efficiency

The energy consumption of CNC worm wheel grinding machine tools is closely related to operation time, machining parameters, the number of workpieces and the structure of machine tools. However, if only consider the instantaneous power consumption and the total energy consumption, it could not reflect the real energy utilization efficiency of grinding machine tools. There are two main methods for evaluating the energy efficiency of machine tools, namely, instantaneous energy efficiency and process energy efficiency [12].

The instantaneous energy efficiency is the rate of the effective energy change and input energy at a certain moment of a mechanical manufacturing system. For grinding machine tool, its instantaneous energy efficiency can be defined as:

$$\eta(t) = \frac{P_m(t)}{P_M(t)} \tag{13}$$

where

$\eta(t)$ the instantaneous energy efficiency
$P_m(t)$ the instantaneous grinding power
$P_M(t)$ the instantaneous total power input.

Process energy efficiency is the ratio of the effective energy consumption of a manufacturing process or a period time and the total energy input of a mechanical manufacture system. Because CNC worm wheel grinding machine tools are mainly used for grinding metal, its effective energy consumption refers to the grinding energy. In the case of a work period from T1 to T2, the process energy efficiency of grinding machine tools can be given by:

$$\xi = \frac{\int_{T_1}^{T_2} P_m(t)dt}{\int_{T_1}^{T_2} P_M(t)dt} = \frac{\int_{T_1}^{T_2} P_m(t)dt}{E_S + E_x + E_y + E_z} \tag{14}$$

Not only can get the value of energy efficiency, but also can analyze influential factors of the energy efficiency, the influence degree of the energy flows, and energy sources on energy efficiency. Therefore, it can provides theoretical data for energy saving and optimization of CNC worm wheel machine tools.

5.2 The Prediction of Energy Consumption

Using a certain CNC worm wheel machine tools as an example and assuming that the machine tools adopt single- step processing. If the machining time is t_s, the time of power system operation is t_k, the time of wheel dressing is t_d, and the total machining time is t_m, the calculation method of energy consumption can be written as follows:

$$\begin{aligned} E_M = E_S + E_x + E_y + E_z = \int\limits_{t_s} P_S dt + \int\limits_{t_s} P_x dt + \int\limits_{t_d} (P_S + P_y) dt \\ + \left[\int\limits_{t_s} (P_{cl} + P_{cr} + P_{fl} + P_{os}) dt + \int\limits_{t_k} (P_{fa} + P_{hy} + P_{lu}) dt + P_{li} \cdot t_m \right] \end{aligned} \tag{15}$$

where

P_{cl} the power of cooling system

P_{cr} the power of chip removal system

P_{fl} the power of flushing system

P_{os} the power of oil mist separation system

P_{fa} the power of fans

P_{hy} the power of hydraulic system

P_{lu} the power of lubrication system

P_{li} the power of light system.

Since the processing adopts numerical control, each production time can be obtained from the programs. The power of main driving system, feeding systems and dressing system can be measured by power sensors. Other power parameters can refer to brochure of machining. This application analysis provides solutions of the prediction of energy consumption, but the resolution process has yet to be detailed.

6 Conclusion

The mathematical model of CNC worm wheel machine tools from the view of energy consumption considering the multi-energy-sources features of CNC worm wheel machine tools is analyzed. The conclusions can be drawn from this work:

1. The influence of the processing characteristics and structural features of CNC worm wheel machine tools on the energy consumption and research is studied.
2. Summarize the characteristics of energy consumption from the view of the energy consumption forms and kinds, and established a mathematical model of multi-source energy flows.
3. Research on the energy efficiency assessment method of CNC worm wheel machine tools and explain the significance of using the mathematical model of energy efficiency to evaluate energy utilization efficiency of CNC worm wheel machine tools.
4. Through the case analysis, provide concrete and feasible method for the prediction of energy consumption.

Acknowledgments This work is supported by the National Natural Science Foundation of China for "Research on the Five-Axis Form Grinding Method for Special Shaped Helicoid Based on Envelope to a Two-Parameter Family of Point Vectors" (Grant No. 51375512).

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Fault Status Assessment for Fault Diagnosis of a Multistage Planetary Gear Set Based on Dynamic Simulation and Experimental Analysis

Guoyan Li, Fangyi Li, Dehao Dong, Jianfeng Li, Haohua Liu and Yifan Wang

Abstract This paper aims at extracting and selecting suitable fault features to assess the damage status of planetary gearbox based on simulated and experimental signals. A nonlinear dynamic model of a two-stage planetary gear set is established. For this model, an improved potential energy method is used to calculate the time-varying gear mesh stiffness considering the influence of different crack levels in the sun gear of the second stage. Then, several fault features are provided to assess the crack propagation levels based on the simulated signals. Afterwards, the change percentages of these statistical indicators are compared for evaluating the sensitivity of each fault feature. Finally, the actual vibration data collected from an industrial planetary gearbox with pitting and broken tooth damages are provided to validate the theoretical derivations.

Keywords Multistage compound planetary gear set · Nonlinear dynamic model · Time-varying mesh stiffness · Fault features selection

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1 Introduction

Many industrialized countries need to consider the resource shortage and environmental issue. Scrapped machineries still have high salvage value. So, remanufacturing becomes a best solution to deal with these concerns. Planetary gearboxes are widely used in large-scale and complex mechanical equipments, such as wind turbines, helicopters, construction machineries, and etc. However, the damage statuses of recycled gearboxes are complicated and various due to their different service conditions and geometric structures. Therefore, the fault diagnosis of the recycled objects plays a key role in assuring the remanufactured products' quality.

So far, the common fault features can be divided into the time-domain statistical indicators, the frequency spectrum analysis indicators, and the feature parameters specially designed for gear damage assessment [1, 2]. However, the redundant and irrelevant features will increase the computation burden, impact the classification accuracy, and make the model more complex. Thus, selecting best fault features out of all the indicators becomes a new challenge in recent years. Due to the influence of strong environmental noise, the incipient fault signatures are always too weak to be identified. Moreover, the fault forms and levels are various in practice. So, it's difficult to directly evaluate the effectiveness and sensibility of the fault features through the collected signals. Therefore, model-based dynamic analysis and simulations become important methods to evaluate the fault features. The compound and multistage planetary gear sets are common in construction machineries due to the requirement of more compact structures and complex transmissions [3]. So the vibration signal analysis and fault status assessment should consider more complicated factors.

This paper aims at providing a dynamic model to simulate the corresponding dynamic responses of the two-stage planetary gear system. Based on the simulated signals, the effective and sensitive of 11 features for reflecting the fault status are compared. Finally, the theoretical derivations provided in the simulation are validated based on the actual signals including pitting and broken damage information.

2 Nonlinear Dynamic Model of a Two-Stage Planetary Gear Set

The detailed description about the two-stage planetary gear set analyzed in this section has been presented in previous work [3]. The lumped-parameter dynamic model for the gear set is shown in Fig. 1. Only one of the planet branches located at a random spacing angle is shown for simplicity purpose. Each component j is allowed to translate in x and y directions and rotate around the axis based on a fixed absolute coordinate frame, denoted by x_j, y_j and θ_j (j = the center components c, r, s_1, s_2, and the planets $p_i(\dot{p}_i, \bar{p}_i, \hat{p}_i)$). All the components are assumed to be ideal rigid body with the mass m_j and the mass moment of inertia I_j. In the dynamic model, the gear mesh interfaces are modeled by spring-damping structures. The time-varying mesh

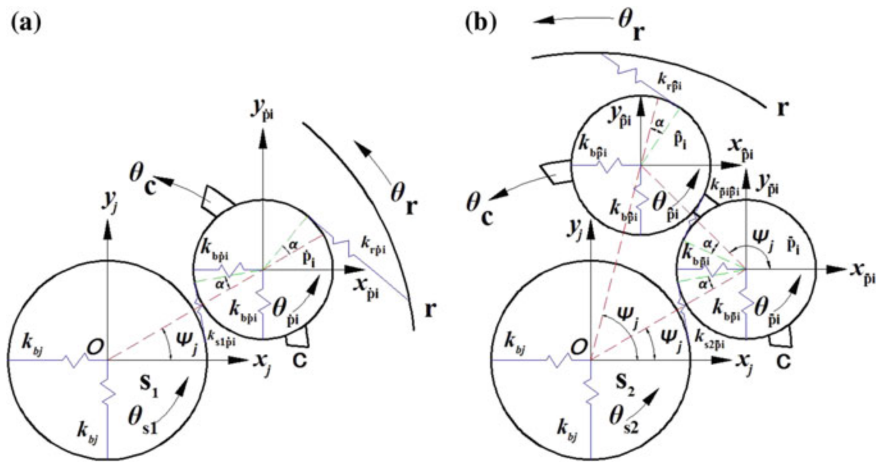

Fig. 1 A lumped-parameter dynamic model for the two-stage planetary gear set

stiffness k_{jpi} is calculated by using improved potential energy method, and the viscous mesh damping coefficient c_{jpi} is set to be proportional to the total mesh stiffness defined as $c_{jpi} = \mu_{jpi} k_{jpi}$ (μ_{jpi} is the scale constant measured in seconds). The linear spring-damping structures are also adopted to represent the bearing supports, where k_{bj} and c_{bj} denote the bearing support stiffness and damping coefficient in radial direction respectively. k_{uj} and c_{uj} are the torsional support stiffness and damping coefficient.

The differential equations for the sun gear, ring gear and planets can be derived as Eqs. (1)–(6) [3]:

$$\begin{cases} m_{s1}\ddot{x}_{s1} - \sum_{i=1}^{N} \sin \varphi_{s1\dot{p}i} F_{s1\dot{p}i} + F_{bs1x} = 0 \\ m_{s1}\ddot{y}_{s1} + \sum_{i=1}^{N} \cos \varphi_{s1\dot{p}i} F_{s1\dot{p}i} + F_{bs1y} = 0 \\ \frac{I_{s1}}{r_{s1}^2}\ddot{u}_{s1} + \sum_{i=1}^{N} F_{s1\dot{p}i} + F_{us1} = 0 \end{cases} \tag{1}$$

$$\begin{cases} m_{s2}\ddot{x}_{s2} - \sum_{i=1}^{N} \sin \varphi_{s2\bar{p}i} F_{s2\bar{p}i} + F_{bs2x} = 0 \\ m_{s2}\ddot{y}_{s2} + \sum_{i=1}^{N} \cos \varphi_{s2\bar{p}i} F_{s2\bar{p}i} + F_{bs2y} = 0 \\ \frac{I_{s2}}{r_{s2}^2}\ddot{u}_{s2} + \sum_{i=1}^{N} F_{s2\bar{p}i} + F_{us2} = \frac{T_{in}}{r_{s2}} \end{cases} \tag{2}$$

$$\begin{cases} m_r\ddot{x}_r + \sum_{i=1}^{N} \sin\varphi_{r\hat{p}i}F_{r\hat{p}i} - \sum_{i=1}^{N} \sin\varphi_{r\dot{p}i}F_{r\dot{p}i} + F_{brx} = 0 \\ m_r\ddot{y}_r - \sum_{i=1}^{N} \cos\varphi_{r\hat{p}i}F_{r\hat{p}i} + \sum_{i=1}^{N} \cos\varphi_{r\dot{p}i}F_{r\dot{p}i} + F_{bry} = 0 \\ \frac{I_r}{r_r^2}\ddot{u}_r - \sum_{i=1}^{N} F_{r\hat{p}i} + \sum_{i=1}^{N} F_{r\dot{p}i} + F_{ur} = 0 \end{cases} \tag{3}$$

$$\begin{cases} m_{\dot{p}i}\ddot{x}_{\dot{p}i} + \sin\varphi_{s1\dot{p}i}F_{s1\dot{p}i} + \sin\varphi_{r\dot{p}i}F_{r\dot{p}i} = 0 \\ m_{\dot{p}i}\ddot{y}_{\dot{p}i} - \cos\varphi_{s1\dot{p}i}F_{s1\dot{p}i} - \cos\varphi_{r\dot{p}i}F_{r\dot{p}i} = 0 \\ \frac{I_{\dot{p}i}}{r_{\dot{p}i}^2}\ddot{u}_{\dot{p}i} + F_{s1\dot{p}i} - F_{r\dot{p}i} = 0 \end{cases} \tag{4}$$

$$\begin{cases} m_{\bar{p}i}\ddot{x}_{\bar{p}i} + \sin\varphi_{\bar{p}i\hat{p}i}F_{\bar{p}i\hat{p}i} + \sin\varphi_{s2\bar{p}i}F_{s2\bar{p}i} = 0 \\ m_{\bar{p}i}\ddot{y}_{\bar{p}i} - \cos\varphi_{\bar{p}i\hat{p}i}F_{\bar{p}i\hat{p}i} - \cos\varphi_{s2\bar{p}i}F_{s2\bar{p}i} = 0 \\ \frac{I_{\bar{p}i}}{r_{\bar{p}i}^2}\ddot{u}_{\bar{p}i} + F_{s2\bar{p}i} - F_{\bar{p}i\hat{p}i} = 0 \end{cases} \tag{5}$$

$$\begin{cases} m_{\hat{p}i}\ddot{x}_{\hat{p}i} - \sin\varphi_{\bar{p}i\hat{p}i}F_{\bar{p}i\hat{p}i} - \sin\varphi_{r\hat{p}i}F_{r\hat{p}i} = 0 \\ m_{\hat{p}i}\ddot{y}_{\hat{p}i} + \cos\varphi_{\bar{p}i\hat{p}i}F_{\bar{p}i\hat{p}i} + \cos\varphi_{r\hat{p}i}F_{r\hat{p}i} = 0 \\ \frac{I_{\hat{p}i}}{r_{\hat{p}i}^2}\ddot{u}_{\hat{p}i} - F_{\bar{p}i\hat{p}i} + F_{r\hat{p}i} = 0 \end{cases} \tag{6}$$

in these equations, the rotational displacement $u_j = r_j\theta_j$ is defined in place of θ_j, where the parameter r_j is the base radius of each gear, and r_c represents the radius from the carrier center to the planet center. F_{jpi} is the dynamic gear mesh force. F_{bjx}, F_{bjy} and F_{uj} represent the bearing forces in x, y and u directions, respectively. δ_{jpi} is the relative gear mesh displacements along the line of action of stage n, and the detailed derivation is provided in Ref. [3].

The mesh stiffness calculation model described in this section is based on the works in Ref. [4–6]. The gear was simplified as the cantilever beam on the root circle. And the improved energy method was used to analyze the time-varying mesh stiffness, which was assumed to include four components: Hertzian energy u_h, bending energy u_b, shear energy u_s and axial compressive energy u_a. The MATLAB programs are used to obtain the total mesh stiffness. Figure 2 shows the mesh stiffness of a sun-planet mesh pair in the second stage as a function of rotation angle of the sun gear. The mesh duration is from the crack sun gear starting to mesh to the ending of mesh. For the perfect sun-planet mesh pair, the mean mesh stiffness is 1.783×10^9 N/m. For local damage case, we assume that a crack starts from the root of sun gear and propagates with an increment of 10 % (the total crack length is set to be 9.42 mm), it's observed that the mean mesh stiffness becomes lower due to the crack. With respect to crack level 10, 20, 30, 40, 50, 60, 70 %, the corresponding mean mesh stiffness are 1.672×10^9, 1.564×10^9, 1.463×10^9, 1.351×10^9, 1.234×10^9, 1.119×10^9, 9.889×10^8 N/m. The reduction will induce to the obvious changes in dynamic responses of the gear set.

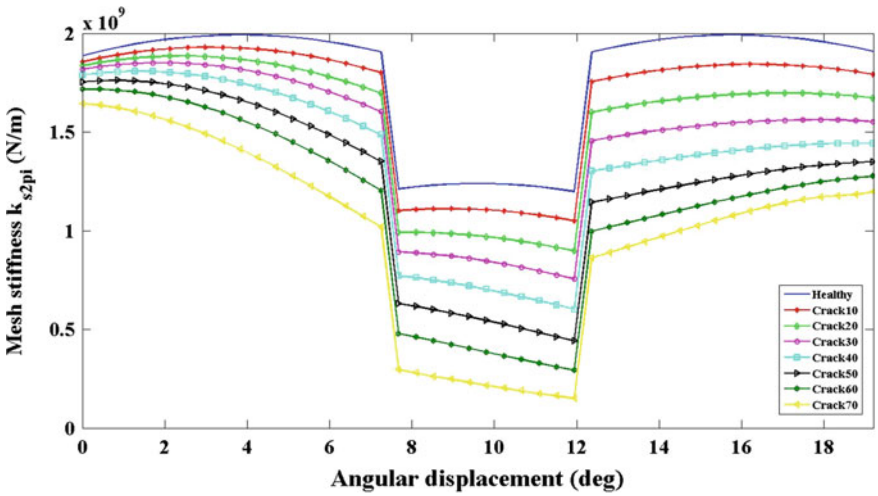

Fig. 2 Total mesh stiffness of the sun-planet mesh pair in the second stage versus angular displacement of sun gear with different crack levels

3 Fault Features Analysis and Crack Level Assessment Based on Dynamic Simulation

In this section, the main parameters used in the simulation are provided in Ref. [3]. And MATLAB's ode15s function is used to solve the equations of motion derived in Sect. 2. The sample frequency and duration time are set to be 5120 Hz and 2 s, respectively. As described above, a crack exists on the sun gear s_2, and propagates from 0 % (the healthy gear set) to 70 % (close to a sudden broken) with an increment rate of 10 %.

In order to focus on the crack status of the sun gear, only the simulated signals of sun gear s_2 are presented in time domain analysis. Figures 3, 4, 5 and 6 show the dynamic responses of the sun gear s_2 in time domain and the corresponding frequency spectra of the system when the crack levels are 0, 30, 50 and 70 %, respectively. For the healthy gear set, the periodic impulses caused by time-varying mesh stiffness are observed in time domain, and the time interval is 0.0055 s. The corresponding spectrum consists of the fundamental meshing frequency of the first stage ($f_1 = 168\,\mathrm{Hz}$), the fundamental meshing frequency of the second stage ($f_2 = 182\,\mathrm{Hz}$), and their harmonics $(kf_1, kf_2(k = 1, 2, \ldots))$. When the cracked sun gear s_2 is in mesh, some other obvious shocks appear in the vibration signals at an impulse period of 0.055 s. And more spectrum peaks appear as sidebands around the frequency components at the frequency of $kf_2 \pm mf_{s2}(k = 1, 2, \ldots, m = 1, 2, \ldots f_{s2} = 18.2\,\mathrm{Hz})$ due to the multiplicative modulation effects caused by the damaged sun gear. As the crack propagates, the amplitudes of these shocks become stronger both in time domain and frequency domain.

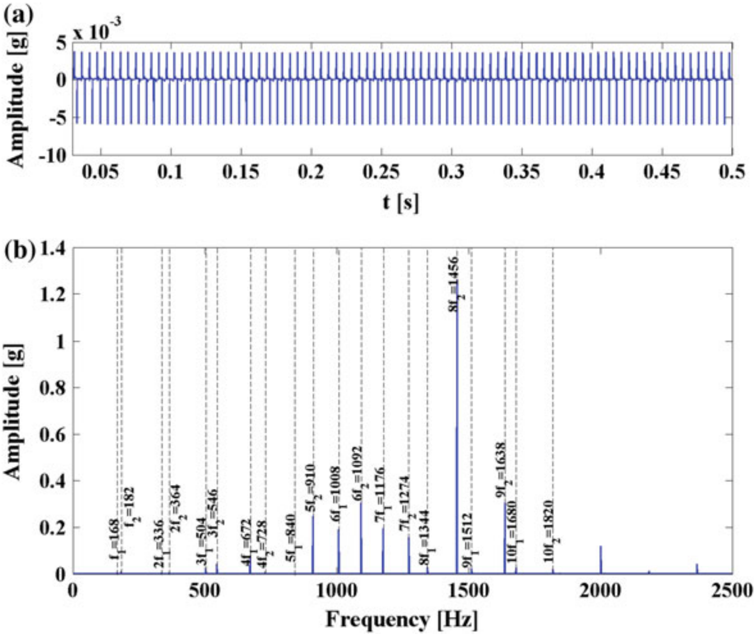

Fig. 3 **a** Dynamic response of the sun gear s_2 in time domain. **b** Frequency spectrum of the system for the healthy gear set

In this section, 11 fault features are selected to assess the crack status as listed in Table 1 [1, 2]. The key is to find out which features are more sensitive to the crack propagation and can be selected to better describe the fault status. To make all the indicators comparable, the change percentage related to the healthy indicators $I_{pj}(j = \mathrm{F1, F2, F3, \ldots, F11})$ are derived as [7–9]:

$$I_{pj} = \frac{I_{\mathrm{damage}j} - I_{\mathrm{healthy}j}}{I_{\mathrm{healthy}j}} \times 100\% \tag{7}$$

in the equation, $I_{\mathrm{damage}j}$ represents the indicator value in the damaged case, and $I_{\mathrm{healthy}j}$ is the indicator value in the healthy case.

Figure 7 shows the calculated results with respect to the crack levels in percentage. The Shape indicator almost has no response to the crack propagation, so it cannot be considered as an effective indicator of fault status. Both in time domain and frequency domain, the RMS and σ have a similar change trend, but the change percentages of these indicators are lower than 30 % even the crack level reaches to 70 %, so they are not sensitive to the crack levels. The performance of the mean frequency is a bit better, and the change percentage is about 56 % related to 70 % crack level. The Crest indicator, Clearance indicator and Impulse indicator keep

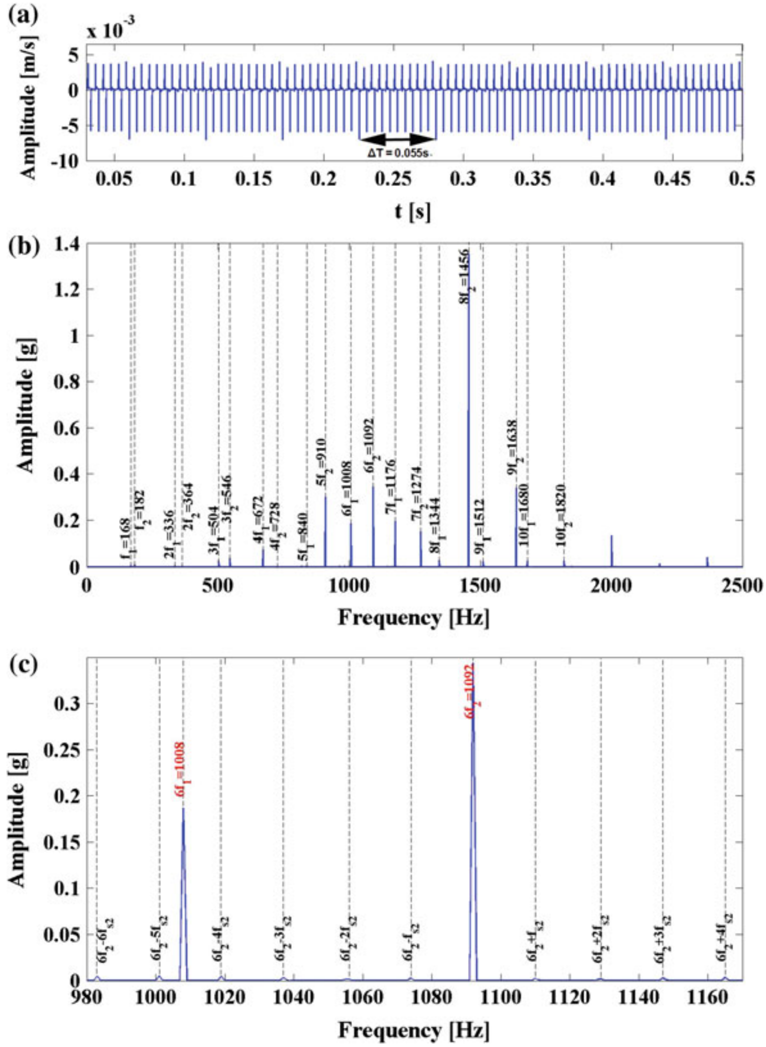

Fig. 4 **a** Dynamic response of the sun gear s_2 in time domain. **b** Frequency spectrum of the system, **c** Enlarged frequency spectrum for the gear set with 30 % crack level

steady increasing pattern as crack propagates, while the Kurtosis and Skewness exhibit a sharp increasing trend when the crack level reaches to 50 %, and the Kurtosis is more sensitive to the severe crack damages. For the slight crack damages ranging from 0 to 30 %, the Crest indicator, Clearance indicator and Impulse indicator show obvious increasing trends, and the Impulse indicator stands out to be the best indicator, but the Kurtosis and Skewness perform bad. So it can be

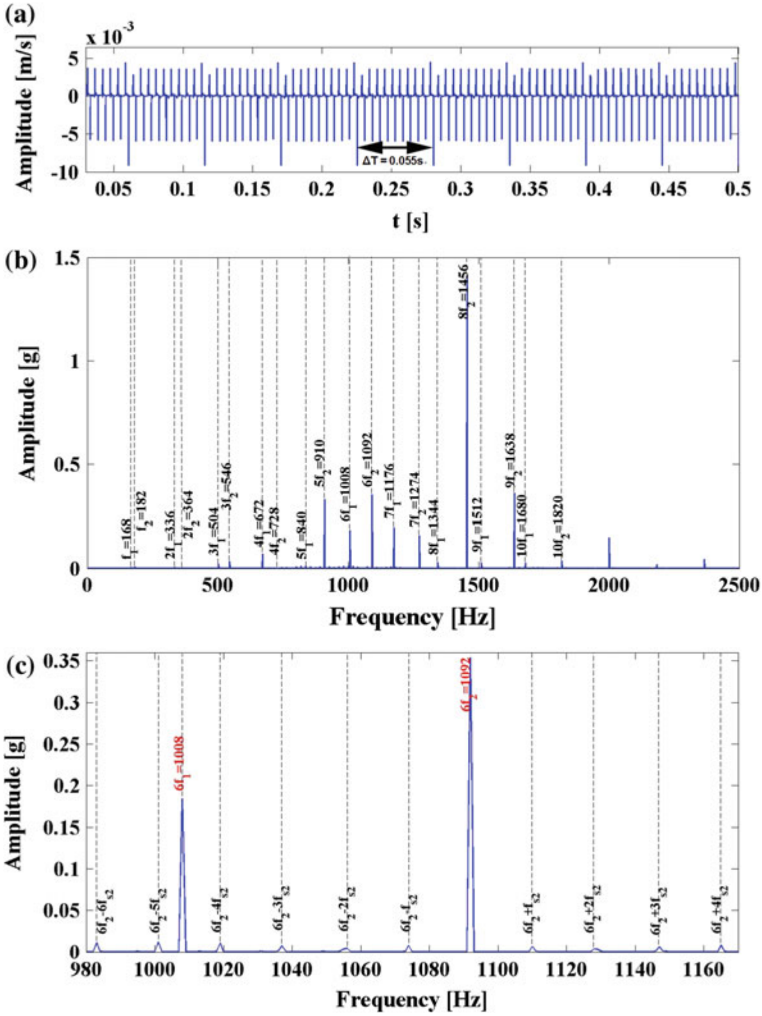

Fig. 5 **a** Dynamic response of the sun gear s_2 in time domain. **b** Frequency spectrum of the system. **c** Enlarged frequency spectrum for the gear set with 50 % crack level

concluded that Crest indicator, Clearance indicator, Impulse indicator and Kurtosis can provide useful information for damage assessment, and Impulse indicator is more sensitive to the early stage faults, while the Kurtosis is more effective when the faults become severe.

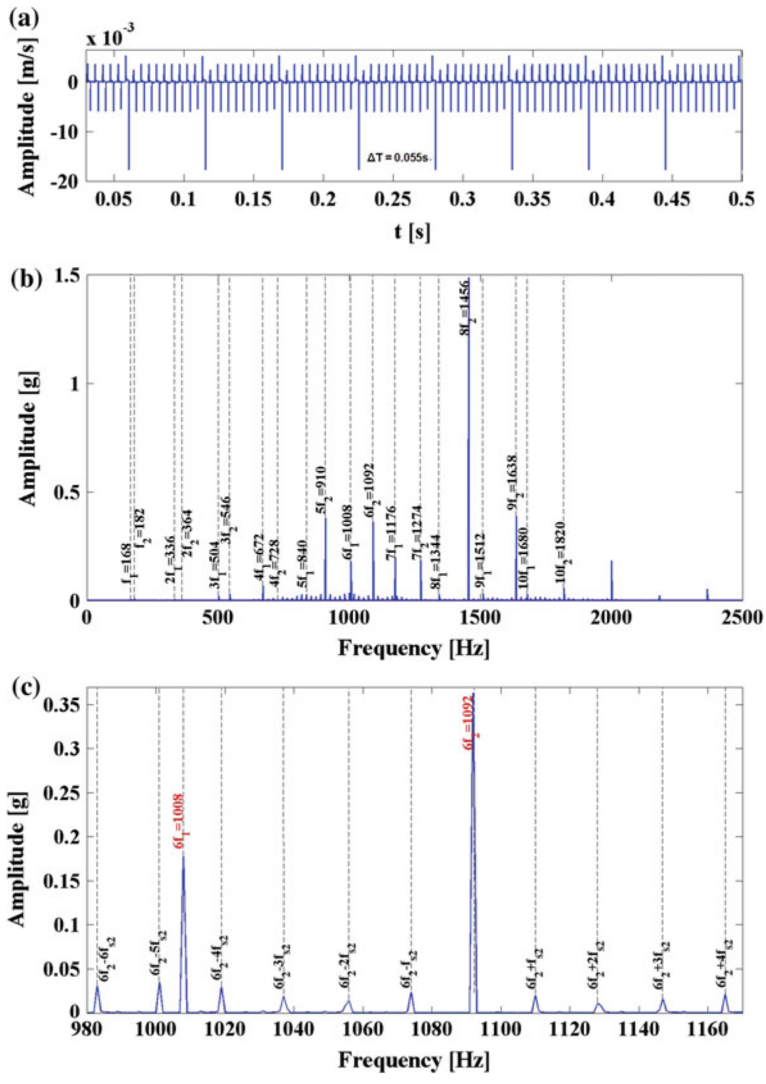

Fig. 6 **a** Dynamic response of the sun gear s_2 in time domain. **b** Frequency spectrum of the system. **c** Enlarged frequency spectrum for the gear set with 70 % crack level

4 Experimental Results

The vibration based experiments have been done on a planetary gearbox test rig, as shown in Fig. 8. The KD1002S three-axis accelerometer is mounted on the test gearbox casing to measure the signals, and the data are recorded by CRAS signal acquire analysis system. The test gearbox is an industrial SD16 planetary gearbox,

Table 1 Definitions of the 11 fault features

	Fault features		Fault features
1	Root mean square	7	Shape indicator
2	Standard deviation	8	Impulse indicator
3	Skewness	9	Mean frequency
4	Kurtosis	10	Root mean square frequency
5	Crest indicator	11	Standard deviation frequency
6	Clearance indicator		

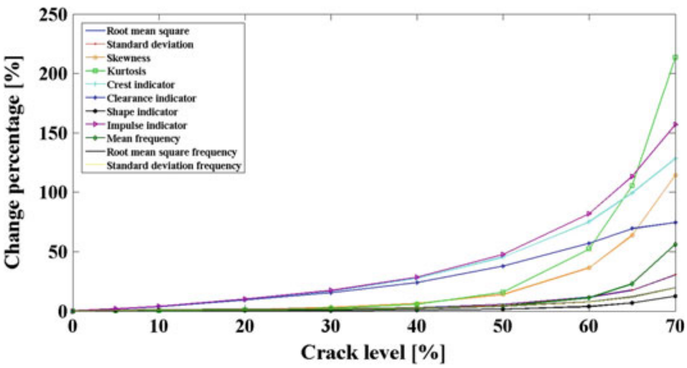

Fig. 7 Comparison among fault features with respect to the crack levels in percentage

as shown in Fig. 9 a, and the system parameters of the second row gear series of this gearbox are the same as the gear model parameter used in the simulation.

To obtain the signal samples, a new sun gear, a pitted sun gear (see Fig. 9b) and a broken sun gear (see Fig. 9c) were considered in the experiments. The vibration signals collected from the new planetary gearbox was considered as baseline level. Then, we mounted the naturally pitted sun gear to replace the perfect sun gear in the second stage to obtain the slight level signals, whereas all the others are normal during the experiment. Similarly, we used a broken sun gear in the second stage to get the severe level signals. During the experiments, the drive motor speed maintained 700 rpm. We considered four load conditions of the load motor: no-load, 200, 600 and 1000 Nm. A 36 s span data was recorded with a sampling frequency of 5120 Hz under each working condition. The same procedures were repeated until three cases were conducted. Each 36 s-long signal was divided into 18 equally time records, so we get 72 signal samples for each damage case under four loading conditions. Figure 10 gives an example of signal samples for each case under the 1000 Nm load condition, respectively.

The change percentages of kurtosis, crest indicator, clearance indicator and impulse indicator selected in the simulation are calculated directly based on each experimental signal sample, as shown in Fig. 11. It can be observed that the mean value of all these features become higher as the damage status becomes worse, so

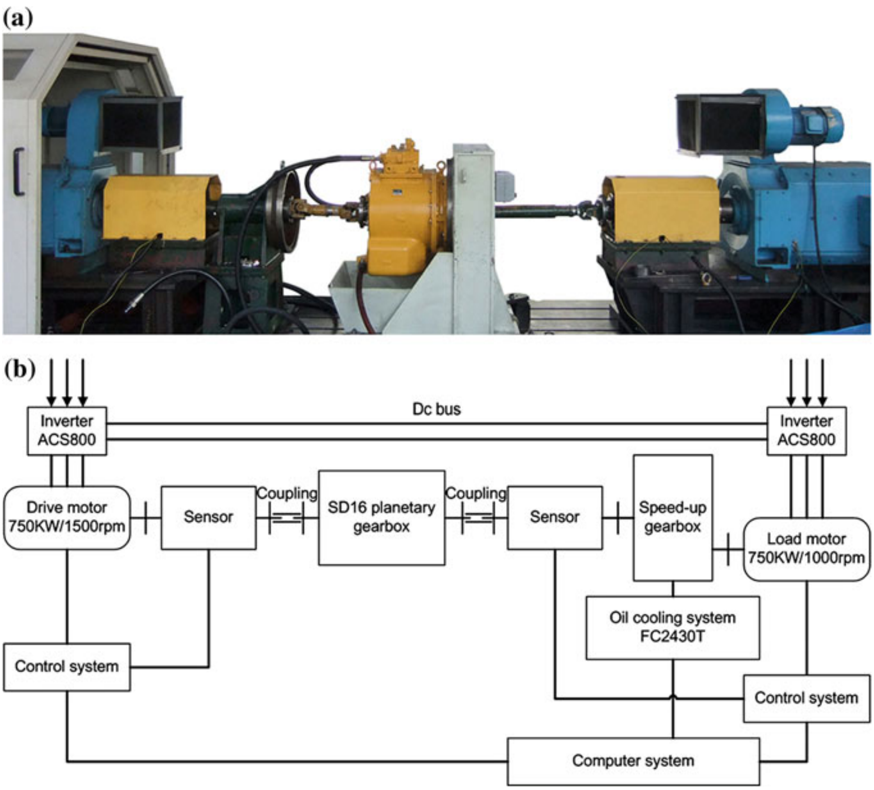

Fig. 8 **a** Planetary gearbox test rig. **b** Structure diagram of the test rig

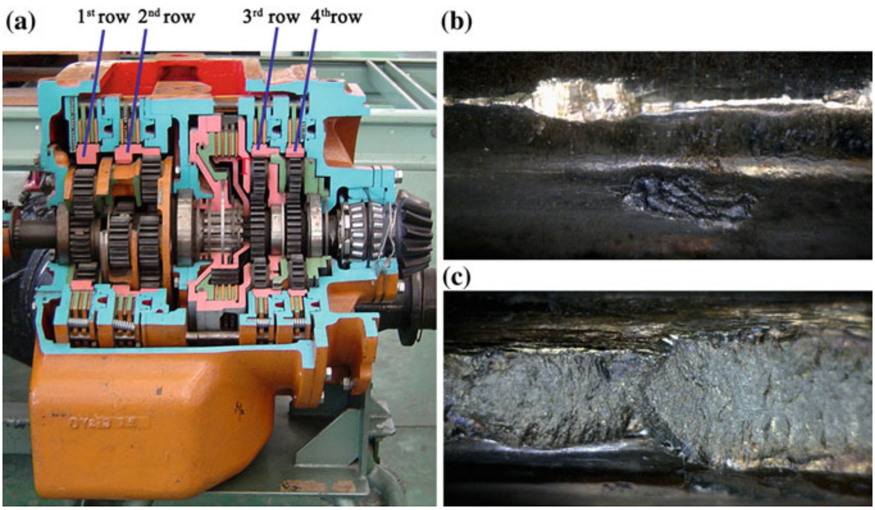

Fig. 9 **a** SD16 planetary gearbox. **b** Pitted sun gear s_2. **c** Sun gear s_2 with broken tooth

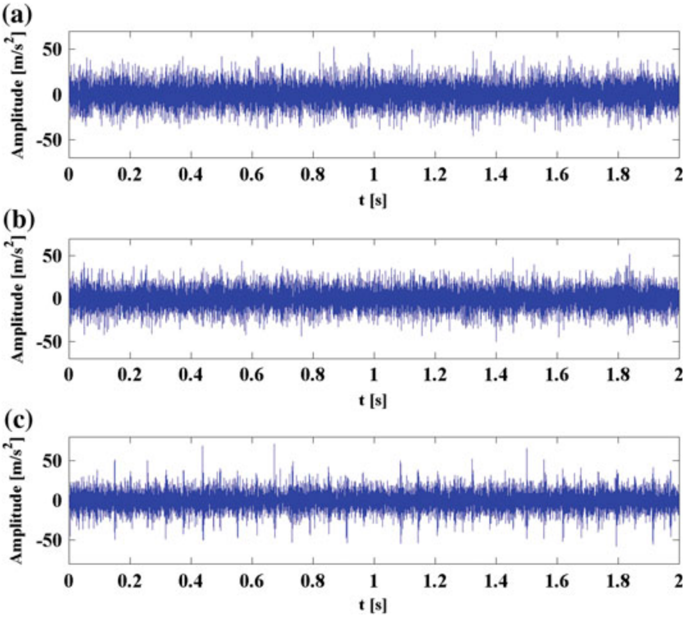

Fig. 10 Typical signal samples **a** new gearbox case, **b** pitted sun gear case, **c** broken sun gear case under 1000 Nm load condition

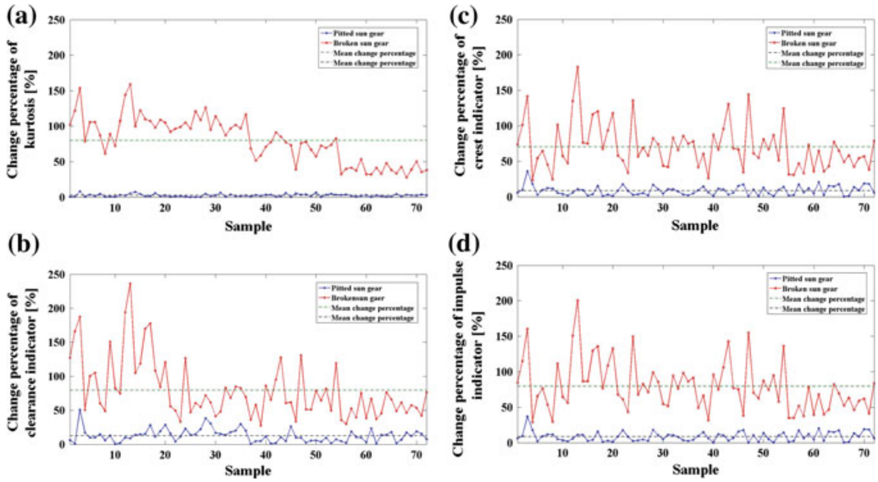

Fig. 11 Assessment results of **a** Kurtosis. **b** Crest indicator. **c** Clearance indicator. **d** Impulse indicator

they can effectively distinguish the fault samples for different damage severity. However, the Crest indicator, Clearance indicator and Impulse indicator are more sensitive to reflect the damage in their early stage than Kurtosis. All the features fluctuate with the change of work conditions.

5 Conclusions

In this paper, a nonlinear dynamic model of a two-stage planetary gear set considering the time-varying mesh stiffness has been established. A crack propagating alone a line is assumed to exist on the sun gear in the second stage, and the corresponding vibration signals are obtained. Several fault features are investigated to evaluate the crack status based on the dynamic simulated signals. It suggests that the kurtosis, crest indicator, clearance indicator and impulse indicator are more effective features for fault status assessment, and all keep increasing pattern as crack propagates. But the crest indicator, clearance indicator and impulse indicator are more sensitive to the early stage faults, while the kurtosis is more sensitive when the faults become severe. The actual test signal samples acquired from the experimental system are used to demonstrate the effectiveness of the proposed fault features for the different gear faults. It suggests that the kurtosis, crest indicator, clearance indicator and impulse indicator can absolutely distinguish the different fault status, and keep increasing trend as the fault becomes severe.

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