Smart, Eco-Sustainable and Human-Centered Product Development Processes: 21st Century Manufacturing Industries

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Abstract The development of new and valuable products, from conceptual design to production, is to date supported by advanced methodologies based on ICT tools allowing many controls and checks before proceeding to heavy spending investment decisions. The increasing use ICT allow highlighting product design process and solutions able to improve people's quality of life. Key product development principles based on human-centered approaches and eco-sustainability concepts prove to be the main factors affecting both the products' users as well as the product manufacturing staff. This paper outlines product's development approaches state of the art, foreseeing at the same time possible research trajectories to define manufacturing industry future scenario based on more sustainable economical, environmental and social design choices.

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1 Introduction

Economic, environmental and social sustainability of companies is a steadily growing challenge for the global business community. The sustainability models form the basis for the advice the companies provide and for decision-making. In particular, many companies try to implement the principles of sustainability in their organizational culture by adopting international standards and management systems, (e.g. Global Reporting Initiative [15]) guideline, ISO 14001, 9001, OHSAS 18001 and Social Accountability 8000 standard (SA8000). These guidelines and frameworks have gained in popularity over the last decades and they have been key components in the corporate strategic management and decision-making process [4, 32].

An area of particular interest for sustainability, which receives heightened interest concerns the impacts of products and services on people and the environment [27]. In particular, the life cycle thinking is a suitable approach for evaluating impacts derived from the behavior of all players involved in the life cycle of products [9]. In the context of life cycle thinking, the three basic dimensions of sustainable development (i.e. environmental, social and economic dimensions) have been identified and various methodologies and tools have been proposed. Specifically, Life Cycle Assessment (LCA) methodology has been developed in order to analyze the environmental impacts of a product's life cycle, while Social Life Cycle Assessment (SLCA) and Life Cycle Costing (LCC) methodologies evaluate the social and economic impacts of products, respectively.

The aforementioned methodologies have not been developed at the same rate. In particular, Social LCA is not fully developed and many authors stress that there is plenty of room for progress in this area [35]. According to [37], the main weaknesses of the SLCA approach are connected to the selection of the appropriate data and social indicators, the inclusion of stakeholder groups and impact categories as well as issues regarding the impact assessment methods.

The relevance of social impact assessment is particularly stressed if regarded the sustainable manufacturing in the widest context of sustainable development. In fact, as it well known, sustainable development must be regarded in as meeting the need of the current generation without compromise the possibility for future generations to satisfy their owns [6].

This anthropocentric perspective leads to joint objectives in particular between ergonomics/human factors and sustainable manufacturing. In fact, if social sustainability is realized in general through concepts such as preventive occupational health and safety, human-centered design of work, empowerment, individual and collective learning, employee participation, or work-life-balance [18] the sustainability of human resources based on enduring workability and employability have always been dominant elements in ergonomics/human factors. Consequently, the implementation of ergonomics in the product life cycle might support productivity and quality, promote the health of employees and improve competitiveness [19].

In this context, the present work aims to highlight the main approaches described in literature then a critical analysis of research open issues for the 2050 scenario is reported.

2 Life Cycle Approaches in Sustainable Product Development: State of the Art

A sustainable product development process should be based on three pillars: social, environmental and economic (Fig. 1). The following literature review is structured with the aim of emphasising and analysing such pillars.

2.1 Social Life Cycle Assessment

Social Life Cycle Assessment (SLCA) is defined as an effective technique useful to analyze social and social-economic aspects that influence different stakeholder groups. These social-economic aspects are linked to products and consequently with the production processes and other business practices which take place along the life cycle of a specific product.

The increasing interest in SLCA methodology has led to a growing body of literature that discusses the applicability and the usefulness of SLCA methodologies for assessing the social impacts connected to the life cycle of a product [20]. Some authors (e.g. [26]) developed theoretical approaches that examine different methodological issues in order to improve the effectiveness of the Social LCA methodology.

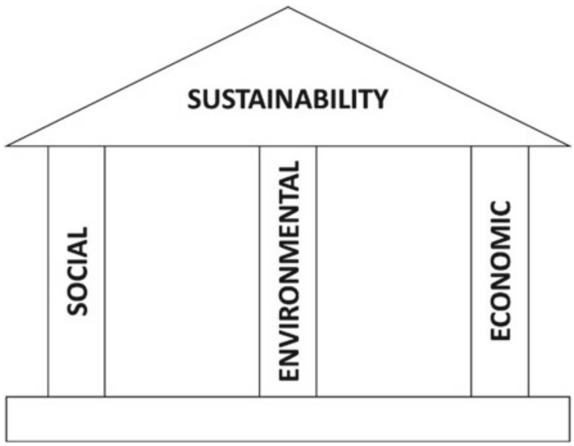

Fig. 1 The three pillars of sustainability

Reference [10] discussed the possible challenges and constraints derived from the implementation of SLCA in product-services systems (PSS). They suggested a "multicriteria indicator model" in order to evaluate social impacts of products. Reference [28] proposed a system dynamic approach to assist in facilitating stakeholders' participation in SLCA methods. A causal model and scenario-based methodology are defined to facilitate the integration of stakeholders' views in product life cycle thinking.

Many authors suggest several indicators to measure life cycle stages and social aspects. Reference [21] stress the importance of measuring aspects concerning the impacts of unemployment on production (e.g. physical and mental health problems, salary reduction) and on workers (e.g. skill degradation). Reference [17] developed a range of socio-economic indicators that are based on three criteria: relevance, practicability and validity. Some of these indicators are gendered labor costs, migrant labor costs, fair wages and discrimination. Reference [21] identified some methods to measure problems associated with child labor and developed essential indicators to improve.

Many authors (e.g. [37]) provide different case studies of the SLCA implementation that show the applicability of SLCA methodological frameworks to a wide range of products from different sectors and for diverse purposes.

An important aspect of social impact in manufacturing is related to human well-being (cognitive and physical) during their daily work. Ergonomics refers to the scientific discipline concerned with the understanding of interactions between humans and technologies, to make tasks, devices, interfaces, equipment and environments compatible with the needs, abilities and limitations of people and therefore to optimize this interaction to create the best working conditions. In the last decade it has been demonstrated how human factors highly affects the global efficiency and costs of industrial processes, from material handling to assembly, order picking or operations in line [3]. Low attention to human factors brings to unnatural positions and dangerous actions executed by workers during their jobs, with consequent lower performances, higher production time, greater absence from work, and a general increase of Musculoskeletal Disorders (MSDs), but also significant mental problems as depression. Understanding real MSD risks, especially related to manual tasks, represents a crucial objective. Given the quantity and complexity of the activities that an operator has to perform, to support the achievement of this objective can be very useful to implement systems that allow a constant monitoring of the operators during the working phases. To this end, in the last years, wearable and environmental sensing technologies aim to provide solutions able to observe the human behavior in order to identify problems and optimize roles [30]. The anthropocentric perspective cannot leave the Industrial and organizational Psychology out of consideration. The discipline is very wide and rich, and it covers a variety of specialty areas and many relevant issues. Job analysis is one the most relevant. It is the collection and analysis of the current work activities that is the starting point for their improvement. Job analysis methods include work-oriented methods, which seek to understand and describe the job in terms of the outcomes and the activities, and worker-oriented methods, which seek to detect the personal features required to successfully performing a job.

In recent years, many authors prefer to use the term "work analysis" instead of "job analysis". This change reflects a new focus on innovation and a distance from the rigid definition of job boundaries. The cognitive work analysis (CWA) provides an interesting approach to design and analyze complex sociotechnical systems [11] and integrate the concepts of cognitive awareness and human behavior.

2.2 Environmental Sustainability

In the recent years, the concept of sustainable product design and development is gaining more attention in research since the pressure for achieving sustainability objectives [2]. The environmental awareness is becoming a fundamental product design driver for a wide number of industries [14], through both legislative issues and market pressure.

Traditional design methods and software tools (e.g. CAD, CAE) are not effective solutions for supporting designers during environmental analyses. To overcome this limitation, several eco-design tools have been developed. Some solutions supply only qualitative results and are too general to be effectively used (e.g. checklists). Other tools require large amounts of data and time for application (e.g. Life Cycle Assessment tools). The analysis of such software solutions highlights the lack of effective integration between eco-design tools and traditional ones [31].

Since the environmental load of a product/service should be evaluated throughout its life span, it is possible to identify four main distinct research areas: (i) materials, (ii) manufacturing, (iii) end-of-life (EoL) and (iv) transport.

1. Sustainable materials are related to a research topic that is very common. Renewable materials can be manufactured or generated quickly to keep pace with depletion rate [8]. These materials, which can be produced without depleting non-renewable resources, are made from natural products or synthetically produced.
2. Sustainable Manufacturing (SM) aims at the development of industrial processes towards a more responsible use of natural resources as well as the integration of ecological aspects in the production processes [29]. SM practice requires a holistic view that covers multiple disciplines: (i) product design, (ii) process design and operational principles, (iii) material/energy/waste flow analysis, (iv) supply chain management and, (v) optimization and planning of production activities.
3. Product EoL and the appropriate management of industrial wastes is a key aspect for sustainable products [12]. Many studies in the literature focus on the detailed assessment and comparison of different EoL treatments [1] and optimization of EoL processes [22]. Even if such studies aim to improve the EoL treatments of post-consumer wastes, these ones do not suggest any solution for improving products at the design stage.
4. Transportation of goods consumes a significant amount of resources. Also, population growth and economic expansion create a bottleneck on transportation

systems, and thus sustainability of transportation is critical in delivering social and economic demand without sacrificing the environment [7].

The Circular Economy is considered as a global economic model for decoupling economic growth and development from the consumption of finite resources. It is recognized as the best economic model to efficiently face the rapid growth of world population and raw material consumption. To date, there are several pilot projects all over the world demonstrating the practical advantages (recycling of Waste of Electric and Electronic Equipment—WEEE and remanufacturing for automotive products). The EU (European Union) has issued directives for restricting the use of hazardous substances, which force manufacturers to respect environmental issues (Directives 2000/53/EC, 2002/95/EC and 2012/19/EU by European Parliament and Council).

Moreover, many manufacturing companies are shifting their business from products selling to services selling. In this transition, the take-back practice is one of the key elements for their economic advantages. Recycling processes, indeed, are becoming attractive for their economic potentialities to earn money from wastes, providing also new job opportunities. Furthermore, remanufacturing strategies are becoming even more attractive than recycling ones for their possibility to give a second life to used components. However, the connections between the product design and End-of-Life phase need to be straightened.

2.3 Economic Sustainability

One of the most important driver for the development of competitive products is the cost. Despite most of the companies are focusing at the procurement stage (strategic sourcing) to reduce the cost of a product, around 80% of the final cost is determined at the design stage [25]. The manufacturing/assembly cost is the most important economic indicator to be estimated yet during the design phases to rapidly compare different technical solutions. Design to Cost (DtC) is a methodology that allows designers to achieve cost targets decided by the management team or product leader [5]. The available approaches enable the application of such a methodology in different stages of the product design (from conceptual to detailed design). In addition to DtC, used at design stage, Should Costing is a methodology to determine what a product should cost based on materials, labour, overhead, and profit margin.

While the manufacturing cost considers only the production phase of a product, the Life Cycle Cost (LCC) refers to the total cost (capital and operational expenditures) throughout its life, including planning, design, acquisition and support costs and any other costs directly attributable to owning or using the product [13]. The LCC estimation, at procurement stage, encourages a long-term outlook to the investment decision-making process rather than attempting to save money in the short term. Beyond LCC (or TCO—Total Cost of Ownership), the Total Value of Ownership (TVO) is a methodology of measuring and analysing investments by considering the benefits of a certain good/service and not only the costs.

Despite the importance of estimating and managing the manufacturing cost or life cycle cost during the early design phase of a product, in order to improve the product margins and turnover, companies should implement the Design to Value paradigm (DtV). This is an integrated approach to product development that considers multiple perspectives: (i) what customers want, (ii) what competitors are offering and (iii) what is the costs to manufacture and distribute a product. By adopting DtV, companies are able to redesign their products, including features for promoting sales (value-added features) while eliminating unnecessary features that only serve to drive costs (not-value-added features).

3 Life Cycle Approaches in Sustainable Manufacturing: Research Open Issues for 2050 Scenario

3.1 Open Issues on Social Life Cycle Assessment (SLCA)

Since the publication of UNEP/SETAC guidelines [38, 39], several SLCA frameworks and characterization models have been suggested to assess the social impacts of products globally across various industries.

As the environmental LCA, the SLCA study have to follow four phases: (1) objectives and system boundary definition, (2) life cycle inventory, (3) impact assessment and (4) interpretation. The main difference between LCA and SLCA approaches is the way to measure the impacts. In the SLCA study, the characterization factor is defined in a more qualitative basis and the impact indicators should be established based on the stakeholders, such employees, the local community, society, consumers and the players in the value chain.

According to [36], SLCA is a valuable assessment tool for stakeholders along the process chain to collect data in order to redesign products including their entire process chains from ‘cradle to grave’ in a sustainable way. Reference [24] highlighted that the S-LCA methodology is less mature than environmental and economic ones. However, it should be noted that despite it is not possible to obtain the conclusive answers, this tool presents a great potential to support the decision making process.

We can hypothesize that in the next years many companies will be involved in a business process re-engineering in order to introduce essential information in relation to the social needs of consumers into the products. This implies that product designers will be able to introduce new basic attributes into the design of the current or new products. The SLCA framework encourage producers to design products which will have either less negative social impacts or a high positive impact on society thanks to the integration of stakeholders’ needs into the social life cycle product design. The stakeholders’ point of views allows product designers to have valuable feedback that could help them to design products that are in line with the demands of stakeholders.

Moreover, the SLCA framework could have different practical implications for all actors of the supply chain. For instance, the supplier selection could be carried out according to this approach. Indeed, S-LCA allows developing a model to generate the social suppliers' profiles in order to support the decision-making process. The suggested SLCA aims to turn managers' attention to making their products more socially positive by addressing the needs of different stakeholder groups at a local or global level, instead of focusing only on making products more attractive to consumers or on meeting specific characteristics of consumers' tastes.

Another implication of the SLCA methodology is connected to the phenomenon of asymmetric information that occurs between producers and consumers. As the producers (i.e. companies) have (positive or negative) information regarding the social impact of their products, they do not disseminate such information to their consumers or other groups of stakeholders. A possible reason for this situation accrues from a lack of auditing and communicating systems to inform consumers. On this basis, the SLCA could be the precursor of a modern label for product social impact that temporarily supports the mutual exchange of information between the consumer/customer and companies.

On the other hand, improving the workers' wellbeing in factories is imperative for all companies, not only for the expected cost saving, but also for the higher process efficiency that can be realised due to reduced absenteeism and less frequent interruptions [23]. Traditional approaches are based on monitoring the criticalities and introducing optimizing actions. However, in order to concretely reduce the workers' injuries, illness, falls, and other diseases, higher benefits can be achieved by a more careful and ergonomic workspace. A challenging perspective is to introduce human factors in the design of the workspace and in the process planning, in order to ensure workers' safety and prevent potential risks.

Understanding real Musculoskeletal Disorder (MSD) risks, especially related to manual assembly tasks, represents a crucial objective for industrial manufacturing. Given the quantity and complexity of manual tasks that an operator must remember and perform, to support the achievement of this objective can be very useful to implement systems that allow a constant ergonomics monitoring of the operators during the working phases. At the same time, such systems should be able to support the operators' training and increase their awareness about correctness of their own postures, in order to stimulate them to behave correctly and reduce MSD risks.

The applications proposed in literature are not able to both support the achievement of these tasks. No studies proposed integrated systems able to guide operators in manual assembly tasks and provide them information about their MSD risk exposure. Moreover, the majority of them are not suitable for industrial application, because they require the implementation of invasive devices and they are not adequate for a large-scale use in industrial assembly lines. For example, in literature, there are a lot of studies that compare traditional assembly instructions methods (ex. paper manual), to AR-based applications that exploit several visualization devices (i.e., desktop screens, HMD, smartphone, tablet, projectors). Results highlighted that computer screen is not suitable for productive context, despite it does not have problems of visual occlusion, because it distracts the operator's attention. Wearable devices, in general, resulted invasive for the operator and limit the possibility to focus on short

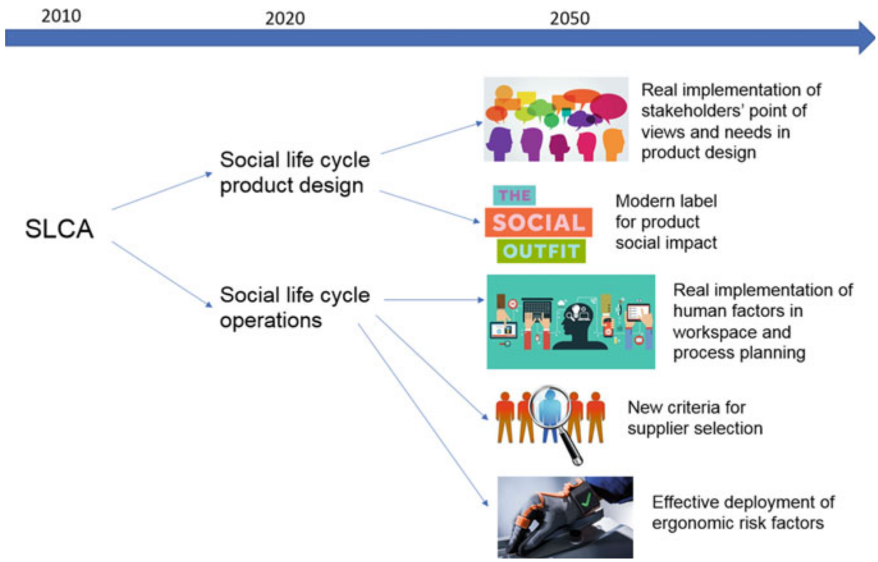

Fig. 2 Open Issues on SLCA

and long distance objects. Anyway, HMD have proved to be more suitable for the operator's training than paper manual and computer screen. Projectors seem to be more efficient, intuitive and fast than other visualization devices, but it can results in information occlusion problems. Consequently, at this time there is still the need of non-invasive solutions capable of effectively and safely support the operator in industrial manufacturing environment.

Another important opened issue concerns the limited methodological research focusing on how to select the most proper tools and technologies to better support ergonomic risk factors assessment and management for the specific context of application. Currently application of proposed methods (i.e. [3]) is very specific and difficultly transferrable to other context, so that companies interested to evaluate the human ergonomics along their processes can only find numerous techniques as checklists and recommendations, without having a precise guideline about the selection of the most proper ones and the joint interpretation of the obtained results. Figure 2 summarizes the main open issue on SLCA for 2050 scenario.

3.2 Open Issues on Environmental Sustainability

Nowadays, Design for Environment approaches are still theoretical concepts, with few industrial virtuous examples (e.g. there are very few applications in SMEs). For example, the academic and industrial state of art do not contain any virtuous approach where the knowledge of dismantlers and recycling centres are formalized and organized in order to be used by designers for the re-design of goods and products. Many case studies demonstrate the advantages of applying eco-design guidelines during the product development but an approach for the dismantlers and remanufacturers knowledge formalization is missing.

Sustainable manufacturing can find new life from the Industry 4.0 and beyond paradigm. Data acquired by monitoring production lines will contribute in identifying environmental hot-spots to be solved, for example, by improving the plant OEE, revamping the assets, reducing or eliminating not-valued-added activities, etc. Future research topics (Fig. 3) are related to four elements of a sustainable business model: value proposition, supply chain, customer and financial justification. From the process point of view, for example, the design of sustainable processes addresses the holistic resource efficiency approach of Industry 4.0 by designing appropriate manufacturing process chains or by using new manufacturing technologies (e.g. additive manufacturing).

The circular economy is a very promising paradigm, but, nowadays, it is still under used. The key-concepts where enterprises and organizations have to focus on are:

- Eliminate the concept of waste: Design products and materials with life cycles that are safe for human health and the environment and that can be reused perpetually through biological and technical metabolisms.
- Power with renewable energy: Maximize the use of renewable energy.
- Respect human and natural systems: Manage water use to maximize quality, promote healthy ecosystems and respect local impacts. Guide operations and stakeholder relationships using social responsibility.

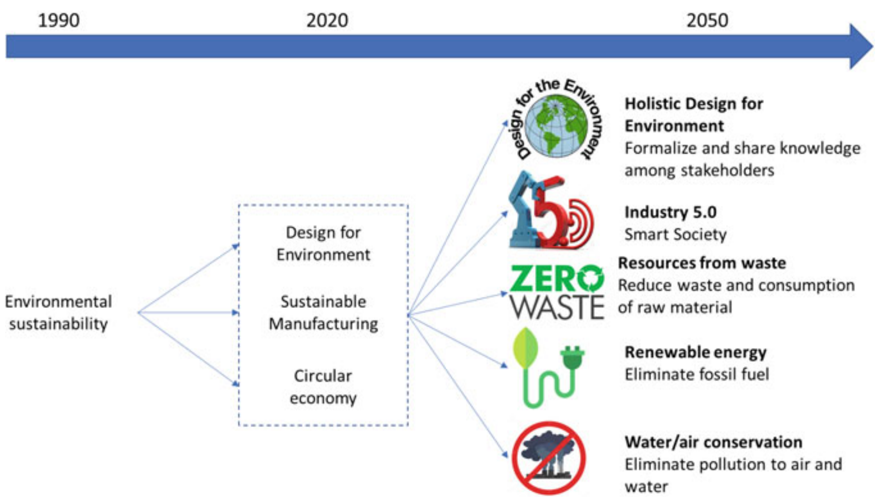

Fig. 3 Open Issues on environmental sustainability

In this framework, additional key concepts to be considered are:

- Decrease in energy and raw material usage combined with reduced emissions and waste generation can tackle a host environmental challenges facing the world.
- Clean manufacturing practices and energy-efficient design of equipment are also hallmarks of environmental sustainability.
- Water conservation is one of the most important environmental issues of this century and growing number of companies are using it to educate and change consumer behavior.

Most of such concepts are also discussed in the "Sustainability and reporting trends in 2025" [15].

3.3 Open Issues on Economic Sustainability

Future research activities (Fig. 4) in the field of the economic sustainability should be mainly oriented in the increase of the effectiveness of the current software tools used throughout the product development process. Despite the wide variety of instruments, their usage is still limited, especially in SMEs. For example, Conceptual Design to Cost approaches and tools are yet far to be widely applied and used within design departments.

Moreover, the models used for the economic analysis should leverage the potentialities made available by the Industry 4.0 paradigm (e.g. Internet of Things, Big Data and Cyber Physical Systems). The real-time analysis of manufacturing data gathered from production lines of the "extended enterprise" will allow designers and production engineers to develop more and more competitive products.

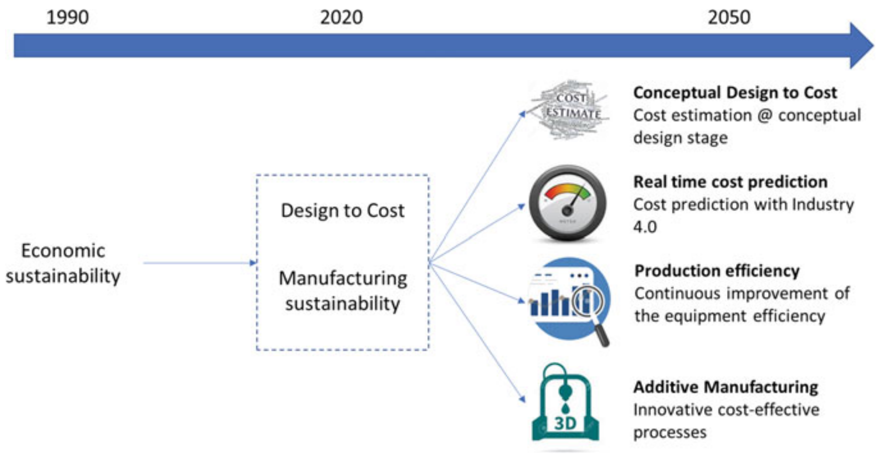

Fig. 4 Open issues on economic sustainability

The adoption of Artificial Intelligence systems for economic analysis will increase their impact on the competitiveness of products and processes. Software tools should be able to optimize the product design, the manufacturing process and the supplying strategy.

The future research related to product/service sustainability should be more and more focused on integrating the three sustainability pillars (economic, environmental and social). Indeed, more companies worldwide are incorporating sustainability into their strategic and operational goals and business planning decisions. Environmental accounting methodologies for collection, measurement, and disclosure of financial and environmental impacts of strategic and operational managerial decisions are used by business entities worldwide for effective management of both organizational and operational environmental protection policies [16]. The correlation among these pillars is also demonstrated by the UN's 17 Sustainable Development Goals (SDGs), which aim to improve the lives of people, increase prosperity, and protect the planet [33].

3.4 A Road Map to Education for Sustainable Development

Education for sustainable development becomes today a strategic objective for the present and for the future and this new national awareness can only begin with schools and students of all ages. Especially by the young, what we could call "environmental natives": a generation that in the everyday life of behaviour already finds as a natural perspective the respect for the environment in which it lives.

Another objective, equally ambitious, is to identify the educational path to sustainable development, so that this is increasingly integrated and convergent in the curricular paths specific to the different orders and degrees of education.

Environmental education, due to the complex nature of the themes dealt with and the need for a holistic approach in dealing with the various themes, cannot be completely exhausted in the treatment within a single discipline by a specific teacher, but it is appropriate instead that it is the result of interdisciplinary paths and coordinated with each other. These concepts are fully applicable in the field of manufacturing process management.

An analysis of recent scientific literature on Education in Sustainable Development (ESD) [34] highlights some interesting experiments discussing the activities of Baltic University Programme and the Mediterranean Universities Network in the field of higher education network organization for the promotion of Sustainable Development.

Sustainable development is a typical interdisciplinary topic including both scientific areas like engineering and humanistic ones like economy, management and politics.

The 2015 United Nations Educational, Scientific and Cultural Organization [40] report deeply analyzed the strategic and fundamental role of instruction organization in the ESD, recognized and one of the seventeen Sustainable Development Goals

(SDG). Teacher's training, under UNESCO point of view, represents a key factor for educators to become active facilitators for ESD.

The recognition of the holistic and interconnected nature of the SDG results in the need to tackle ESD issues from environment, economy and society point of view.

This is particularly relevant for the Italian manufacturing industry, a pillar sector for supporting a prosperous economy and a wealthy society. The transformation process taking place in manufacturing requires several resources whose efficient use can reduce waste as well as minimize impact of transformation processes on the environment. Designers and technicians being aware of Sustainable Development issues will become more and more fundamental for promoting "green" change in the manufacturing companies. The need therefore arises for educational organizations to promote new teaching modules and programs for both students and teachers so that to play a winning role in the international manufacturing competition.

The connection between teaching and research, key aspects of Universities mission, could then be used for academic organizations to provide both professional and students with tailored inter and transdisciplinary competencies, so that to fulfil the different teaching strategies for sustainable development. To this extent it is worth to stress the adoption of an Open Innovation paradigm in the field of Sustainable Development.

4 Conclusions

The paper main scope is to provide the reader with a holistic view of future scenarios and relevant issues in sustainable development in product development and manufacturing. To this extent social, economical and environmental aspects of future potential scenarios have been described trying to highlight possible research trajectories. It is Authors' belief that the three pillars of sustainability will be the main drivers of next decades in all aspects of society to have a better world where people lives. The industrial sector has a great responsibility to realize this objective. One fundamental pillar for a continuous improvement in sustainability awareness is the implementation of education in sustainable development. Systems thinking, interpersonal, integrated problem-solving and critical thinking competencies will be more and more crucial for students and educators to become active player, e.g. people able in learning to know, to do and to be. A strong educational institutions' commitment is thus necessary to design, promote and apply tailored policies for education to sustainable development and content-oriented priorities, defining new curricula with appropriate learning tools compliant with "glocal" cultural aspects.

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