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REVIEW

The implementation of the SBCE principles in the V-cycle steps for the development of a mechatronic product and its production system

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Abstract

The immense integration of electronics, control and software into mechanics has led to considerable technological progress in many sectors like transportation, robotics, aerospace and medicine. Consequently, designing new modern technical products has become costly as well as time-consuming due to the complexity of these products which can bring about frequent design modifications emerging at different design stages of a newly-developed product; hence creating iterative exchange loops among various domains staff. The increase in price and time may not meet the customers' interests and boosts international competition between companies which have always looked for speeding up technological innovation, shortening products life cycle and satisfying customers' expectations in terms of price and quality through mainly adjusting their production systems to speedy, continuous and unexpected changes in customer needs. Thus, production constraints should be incorporated in the early design process phases of a multidisciplinary complex system. Besides, the product as well as the management of the production system need to be concurrently optimized. In this paper, we aim at developing a new approach to decrease the iterative exchange loops and, thus, time and cost and also to improve the quality and the performance of a new mechatronic product. Therefore, we put forward a new approach in which we integrate the SBCE principles into the system engineering approach steps and apply the same principles for the production system development which is to be treated in earlier design steps. The implementation of this approach was performed in a software framework prototype using Python language. Finally, our new method is validated through a case study in the automotive domain. In fact, an Electronic Throttle Body was used for the illustration and validation of this current approach which is meant to help complex system designers to integrate production constraints into preliminary design steps as well as find the most convenient solutions that can enable them avoid heavy costs in the production system.

Keywords Mechatronic product · Product development · Set Based Concurrent Engineering SBCE · System-engineering V-cycle · Production process · Electronic Throttle Body (ETB)

1 Introduction

Technical products have occupied an important part of our daily life. They can be either mechanical, electronic, electromechanical or mechatronic systems. In the past few years, modern technical products have become increasingly complex, thus, they are generally mechatronic ones that are distinguished from other products (traditional mechanical products, electrical product, etc...) owing to their multi-physical as well as multi-disciplinary characteristics in addition to a very high level of integration between mechanics, electronics, control and software. Consequently, mechatronic products are being increasingly used in almost all industrial sectors. Designing such products has, indeed, become a complicated as well as an interdisciplinary task which is also time-consuming due to the emergence of iterative exchange loops in different design stages due to two factors. On the one hand, applying the point-based approach to design a complex system has led to the appearance of iterative exchange loops between designers and other specialists during the evaluation

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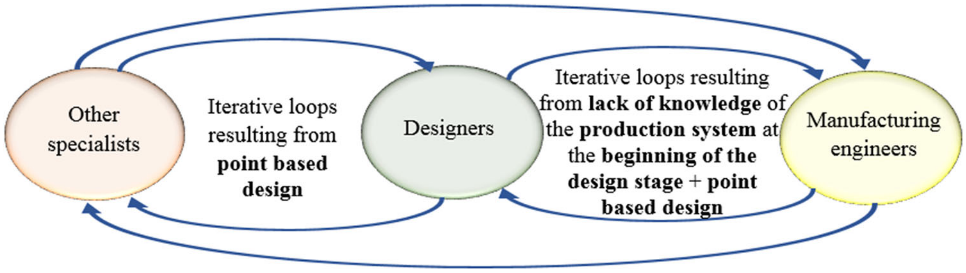


Fig. 1 Iterative Exchange loops

of the system performance. This approach is also based on developing a concept from design space and assessing them whenever a modification emerges until reaching a solution which satisfies the customer's expectations, but not in the best possible way. On the other hand, the lack of knowledge of the production system at the beginning of the design stage led the designers to produce a raw design part characterized by an infeasible or arbitrary geometry. Therefore, iterative loops between manufacturing engineers and designers are generated during the evaluation of the manufacturability of a complex system part due to the interdependency between the product and their production system (Fig. 1).

These loops increase the new products development time and price. For this reason, companies have always argued over the best design method adopted to minimize iterative loops which come about during the development of a new complex system so as to obtain efficient and effective products in relation with various indicators of time, cost, quality, process flexibility, innovation and other indicators [1].

Accordingly, the purpose of our paper is to find out a novel method which can be implemented to satisfy these companies needs. Indeed, a concurrent engineering method is proposed to design complex mechatronic systems. This approach mainly aims at providing stakeholders with a common as well as detailed model starting from the early design stage. It also helps them share the different ideas and analyses with the system engineer. Our proposed method is essentially based on the V-cycle model in which we integrated the SBCE approach principals used for the development of both complex products and their production system as well as the use of the SysML diagrams. On the one hand, the adoption of the SBCE principles intends to reduce not only the delays but also the number of the late modifications. Besides, it helps to develop diversified knowledge about different design concepts, introducing information caused by the performance analyses of the system. On the other hand, the SysML diagrams are utilized to ensure the different constraints traceability and facilitate alternatives communication between the different participants. The approach proposed in this paper responds to the product requirements, its specifications and its manufacturing constraints in order to obtain mechatronic product models and their production system ones in the shortest timeframe and the lowest price. This approach is implemented in a proof of concept application developed with Python and afterwards validated in a case study of an Electronic Throttle Body (ETB).

2 State of the art

Since the 19th century, electronics, software and control have steadily been integrated into mechanics. The term mechatronics was, then, coined in 1969 by Yasakawa to refer to this integration of mecha and tronic which are two abbreviations for mechanics and electronics, respectively [2].

Mechatronics has positively impacted product quality [3]. Indeed, considerable improvements have been recorded. Nevertheless, modern technical products design process has become too complicated as well as expensive in many fields essentially in robotics, transportation and medicine due to the increase in the number of components and sub-systems on the one hand and their interdependency on the other hand.

The product complexity has also led to an unprecedented international rivalry between big companies in order to meet the customers' expectations as to the product quality, space restriction and product cost, increase the innovation speed and reduce the product-life cycle [4].

In order to achieve this aim, most companies have focused mainly on the first design phase that is to say "Conceptual Design Phase" as it requires exorbitant prices and determines nearly 70% of the product performance [5]. During this phase, designers identify customers' needs to get a thorough description of the product to be developed at the level of the global-system which is, itself, divided into subsystems. The division of the global system is achieved at the functional architecture phase. During the next phase, which corresponds to the physical architecture one, a solution or a set of solutions is developed for each sub-system. These solutions are incorporated during the integration phase. The weak integration of the final product sub-systems may be non-functional and is unlikely to meet the system requirements. Thus, reworks, which may be more expensive than the design work done at the beginning of the cycle, must be carried out.

To sum up, it is obviously hard to provide a final product with a high quality, an optimized structure and a moderate

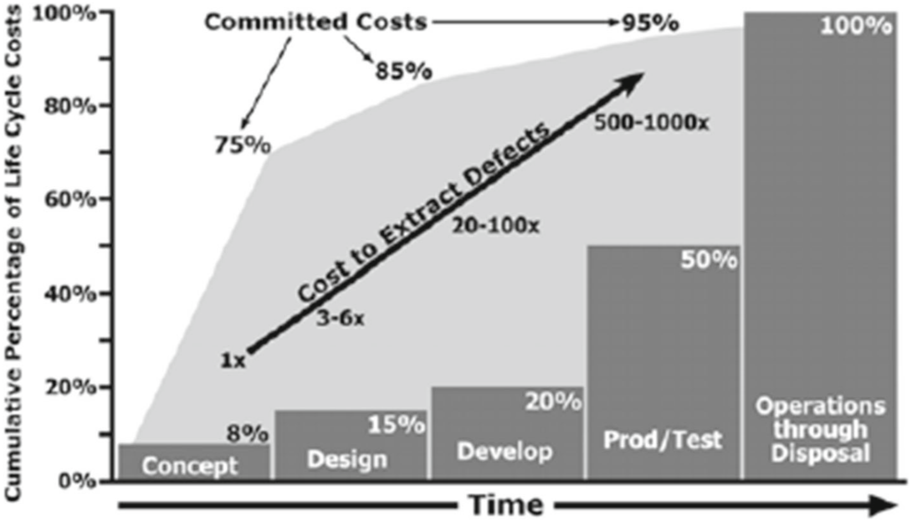


Fig. 2 Commitedlife-cycle cost [7]

price [6]. Figure 2 shows that a new product development cost can increase from 3 to 1000 times whenever a defect takes place depending on the phase during which it is found out.

Collaboration between engineers in all fields in the conceptual design phase is necessary to better control the sub-systems integration problems as soon as possible. In this context, Gero et al. proposed in [8] the FBS model which refers to Function, Behavior, and Structure and presents the design by a group of processes linking the three phases together. Through their model, they showed that the first design process is simply bases on a cartography process which starts with functions and ends with product structures. After that, Authors in [9] suggested a new model called Requirement-Function-Behavior-Structure (RFBS). In their paper, which is mainly based on the works done by [8–10] put forward a new method built on multidisciplinary collaboration formalized during the conceptual design process. Other works also focused on the necessary cooperation between engineers of different fields within the design phase. On the one hand, authors in [11–13] directed their study to rework frequency, cost and size reduction using the DSM matrix in order to cartography the dependencies between the different design parts or various development tasks. This matrix is a square matrix with identical labels found on rows and columns corresponding to the system elements. On the other hand, in their new method proposed in [14], Danilovic and Browing used a DMM triangular matrix having an (n*m) size relating two DSM matrices of two distinctive items, where n is the first DSM matrix size and m is the second. The use of the two matrices has effectively helped to understand the system complexity, reduce uncertainty as well as enhance the knowledge used to analyze the dependencies between the system components. In addition to that, many other works were based on System Engineering defined as a multidisciplinary approach encompassing a set of adequate activities applied to conceive, develop, assess, evaluate and verify the integrated set of solutions in relation to the systems, customers and the process during a whole life cycle so as to eventually meet customers' needs [15, 16]. System Engineering is the most popular approach used in the design process [17] as it allows project teams to develop, verify and validate a complex system giving an efficient as well as economical solution which responds to customers' requirements. Afterwards, this approach has been increasingly linked to the Model-Based (MB) approach for the purpose of developing an integrated and unique methodology applied to integrate simulation and modeling during the design process. Therefore, Model Based System Engineering MBSE [18, 19] provided a substitute for the documentary approach previously applied in system engineering to create complex systems treating various fields and the effects that can emerge during their interactions. Most development models of a complex product are currently based on the V-cycle model [20] which is the most used and known in the system design field as it helps detect the possible defects earlier and, thus, eliminate some of the returns to the preceding phases.

Within this context, OMG (Object Management Group) proposed a SysML model (System Modeling Language) [21–23] utilized in System Engineering to model, specify and decompose complex systems.

Furthermore, other research workers focused on the importance of developing the products and their production system simultaneously so that iterative loops between designers and manufacturing engineers could be reduced. For example, Gausemeir et al. (2011) introduced, in their paper [24], a new model for the development of mechatronic systems and their production ones in a complex design process where the work of multiple-field engineers is interconnected. Authors in [25] further developed the methodology used in

[24] for an integrative conceptual design of modern mechatronic products and their production system. This recent methodology comprises methods applied to analyze and evaluate the costs of product development and manufacturing in addition to robustness to confront the changes as well as the disturbances that can emerge during the design phase. Added to that, to bridge the gap between the distinctive modeling approaches applied for developing products and designing production systems and due to the emergence of numerous interdependencies between product components and production systems, Stellan Gedell et al. modeled these constituents in an integrated model in their work [26]. This model represents the products and their production plants as two equal systems having subsystems, interactions and behavior. In this same model, each sub-system is modeled in all life-cycle steps and the cause behind the design of the product is shown. A class model is then refined in order to form a structured basis for modeling which can itself be used in a computer-based support.

All the previously mentioned tools, approaches and models implemented in complex product development or in product and their production system development are built on the traditional approach named "Point-Based" PB design [27]. Indeed, this approach consists in choosing only one alternative from solution space and then making the appropriate modifications whenever engineers face problems in their analysis domains. In the point-based design approach, one appropriate solution is given to each function based on its characteristics able to be applied in the following stage.

As cited by Sobek et al. [27] the PB approach is made up of 5 steps:

- Problem definition: it can be achieved through understanding customers' needs and establishing product requirements.
- Generating alternatives: designers from each field individually generate a set of possible alternatives.
- Preliminary analysis: at this stage, engineers analyze the brainstormed alternatives in order to pick up the most appropriate and effective solution to be used later in the following development stage.
- Meeting the product goals and development: this stage consists in modifying the selected solution until meeting the product's requirements and goals.
- Repeating from step 1 or 2: the process restarts from step 1 or 2, in case of failure, in order to find the required solution.

These phases aim at reaching the best solution among the possible alternatives as earlier as possible within the shortest period of time. It is, therefore, needless to develop other alternatives. If the selected solution doesn't meet customers' needs, it is modified as soon as possible or is totally replaced by a new solution. Consequently, one solution to satisfy the customer's needs is realized at the end of the development process. Yet, this solution is not necessarily the most optimized one or may fail to meet the customer's needs and requires another solution. Consecutive resets and modifications caused by the lack of communication as well as integration, may result in possible side-effects. The use of the best solution instead of possible solutions, unawareness of efficient solution feasibility and the lack of convergence can also lead to many drawbacks which cannot be ignored. Some of these drawbacks are the increased cost and long development time since the process returns to its initial stages whenever necessary. In brief, all the previously cited methods, approaches and tools which are built on the Point-Based approach are not enough to create complex products with low prices and in a short development time.

Subsequently, to put an end to all the problems created by the point-based approach, notably the repetitions and iterations, Toyota has adopted a new method based on the development of a set of possible solutions for each function. Afterwards, this same method was named Set Based Concurrent Engineering SBCE by Ward et al. [28] in their studies of Toyota product development systems. Their approach consists in evaluating a large set of possible solutions gradually suggested by engineers of different sectors and then selecting the most appropriate ones till reaching the solution that best responds to customer's needs. This approach can be summed up in three steps. In the first step named 'Map the design space', developers meticulously look for possible solutions for each sub-system while defining possible regions and designing different alternatives aiming at exploring the trade-offs and then communicating the set of possibilities.

The second step called 'Integrate by intersection consists in integrating multiple solutions seeking possible intersections for solutions matching each other, laying the maximum constraints as well as searching conceptual robustness. Eventually, the 'Establish feasibility before commitment' step involves reducing, bit by bit, the number of possibilities and simultaneously increasing requirements, sticking to them and converging towards the most appropriate solution (Fig. 3).

The implementation of the SBCE approach will certainly be beneficial for firms. This approach hopefully permits developers to explore the most optimized solutions that can respond to customers' needs and also explicitly discuss the set of possible solutions. Moreover, it helps them reduce project failure rate and avoid the causes of costly reworks. These are likely to emerge in late development stages while developing multiple solutions, improving competence and ameliorating experience. This occurs when evaluating whether or not these multiple solutions need to be retained and managing the risks by simultaneously developing many solutions like innovative solutions and backup ones. The SBCE approach is, thus, more and more used in designing mechatronic systems thanks to its various premises

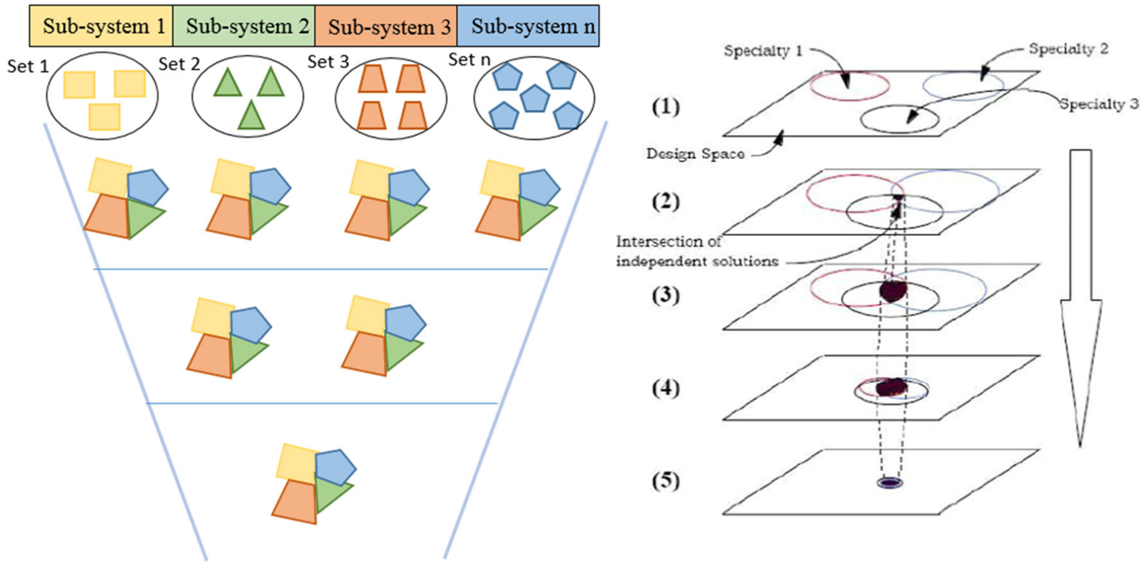


Fig. 3 Set Based Concurrent Engineering SBCE

[29–34], especially the fact that the solutions which are not retained are not definitely rejected but preserved for they can be used in future studies. Furthermore, the rewords offered by the SBCE approach are supported by Toyota, which has become the leading company in the world's auto industry and which is offering high-quality products in terms of developing complex systems in the shortest period of time. Hence, Toyota is currently dominating the car industry because of implementing the SBCE approach and the Quality one [27, 28]. Yet, many companies consider this approach as inefficient for developing novel products due to the variables high number and the use of numerous concepts. It's therefore believed that applying this model is more expensive and it can increase the product development process delivery time [35–37]. This assumption is essentially explained by the lack of knowledge about the way companies establish the design process and organization to create new products with a set based design.

Based on the literature, we draw a table in which we compare previous works to highlight the strengths and weakness of each contribution (Table 1).

The different studies based on the MBSE principles [38–42] support the use of this model as it, first and foremost, helps link the different disciplines, handle the data shared by those taking part in the product design, reduce ambiguities, save time, decrease the design cost and fully as well as coherently represent the different development phases. Yet, almost all the works founded on the MBSE principles were themselves based on the point-Based design. This prevents designers from developing an optimal solution.

Besides, other works opted for the SBCE approach [6, 43–48] as it helps stimulate teams by reusing the approved

Table 1 Table of evaluation of development models

	Ensure the continuity of the design and the traceability process between the different development phases	Reduce the iterative loops of the product design or of its production system	Facilitate collaboration between the different stakeholders in the development process of the product or its production system	Allow designers to quickly find an optimal solution or to identify the non-existence of it	Promote integration between the product development and its production system
MBSE	Yes	No	Yes	No	Partially
SBCE	Partially	Yes	Yes	Yes	No
Integration between product development and its production system	Partially	Yes	Partially	No	Yes

sub-set solutions through maintaining the solutions rejected in previous work to be reused in future studies. The reuse of the acquired, structured and stored data is beneficial as it contributes to saving time, price and effort in the design phase. Added to this, it establishes an interdisciplinary knowledge exchange such as the information shared for storage.

Added to all these advantages, this approach facilitates collaboration between all the participants by identifying all the stakeholders and taking into consideration all constrains in the preliminary design phases. Furthermore, the SBCE principals process help reasonably and collectively choose the best adapted solution offering the best traceability between the solution and the needs to be met, which helps revise requirements and integrate new needs at any moment.

Nevertheless, although many works were based on the MBSE and SBCE approaches, a few considered integrating the production constraints in the preliminary design phases. This defect generally leads some designers to return to the preceding design phases, in late development stages (production phase) and after the development of the final system solution design, in order to modify the development solution and , thus, meet the requirements of production engineers adding other production constraints.

The models suggested in these few works [24–26, 49–52] facilitate the integration of the product development into its production system regardless of the simplification of the collaboration between the various stakeholders in the product development process.

Besides, the system solution in these works hardly respects the production constraints and meets the customers' needs.

To sum up, because neither of these methods totally satisfies the defined criteria, we adopted a new approach where the SBCE principals are incorporated into the MBSE method for the product/ production system development through the integration of this latter in the preliminary design phases. This approach allows engineers to include many aspects so as to reduce the production time, boost the system performance right from the preliminary design phases, manage the data shared by the design participants and obtain an optimal system solution. Furthermore, it aims at reducing iterative loops between designers, manufacturing engineers as well as other specialists. These iterative loops are responsible for delaying and increasing novel products development costs.

3 Methodology

The design process is generally divided into three essential parts which are the conceptual design phase, the detailed design one and the production phase. Most researchers have claimed that 70% of product design cost and performance are involved in the initial design stage. As a consequence, our method developed in this paper revolves around the conceptual design phase to prepare the necessary data which will be used later on during the two following stages in order to reduce iterative loops which may occur during the whole development process. Our proposed method is summed up in the Fig. 4.

As shown in the figure above, we essentially started with the system engineering V-cycle integrating the Set-Based Concurrent Engineering Principles for the development of a new product and its production system. This latter is incorporated in the design preliminary phases so as to reduce iterative loops; between designers and manufacturing engineers; emerging mostly in late design phases.

3.1 Steps (1) (2) (3) (4) (5) and (6)

To develop a new complex system, we first understand customers' needs and specify requirements. These needs should be organized and classified as key Value Attributes (KVA) through the Analytical Hierarchy Process (AHP) [53], then placed in a VE vector which should be organized in a decreasing order were ε1 et q represent the most important percentage and the requirements number, respectively.

$$VE_q = \begin{pmatrix} \varepsilon_1 \\ \vdots \\ \varepsilon_q \end{pmatrix}$$

Second, we define the system functional architecture and its decomposition into sub-systems. In the third stage, we use the SBCE approach to develop the system physical architecture in which we propose a set of possible solutions for each sub-system related to a specific function. Then, these solutions are integrated by intersection to constitute the physical solution system. The results produced from these steps are transformed into data matrices which are exploited later on by our first algorithm developed in the first paper [53] which aimed at finding the number of possible solutions for the design problem and reducing their number. We relied on mathematical equations developed in [53] to reduce the number of possible solutions basing ourselves on the clients' requirements and the criteria of each sub-system possible solutions. Indeed, a priority percentage for each need is given using AHP and weights from 1 to 5 are allocated to each sub-system solution in accordance to each requirement in the form of a DMM matrix named R_{yq}. The weights are allocated according to experts knowledge, literature, communication and certain simulations.

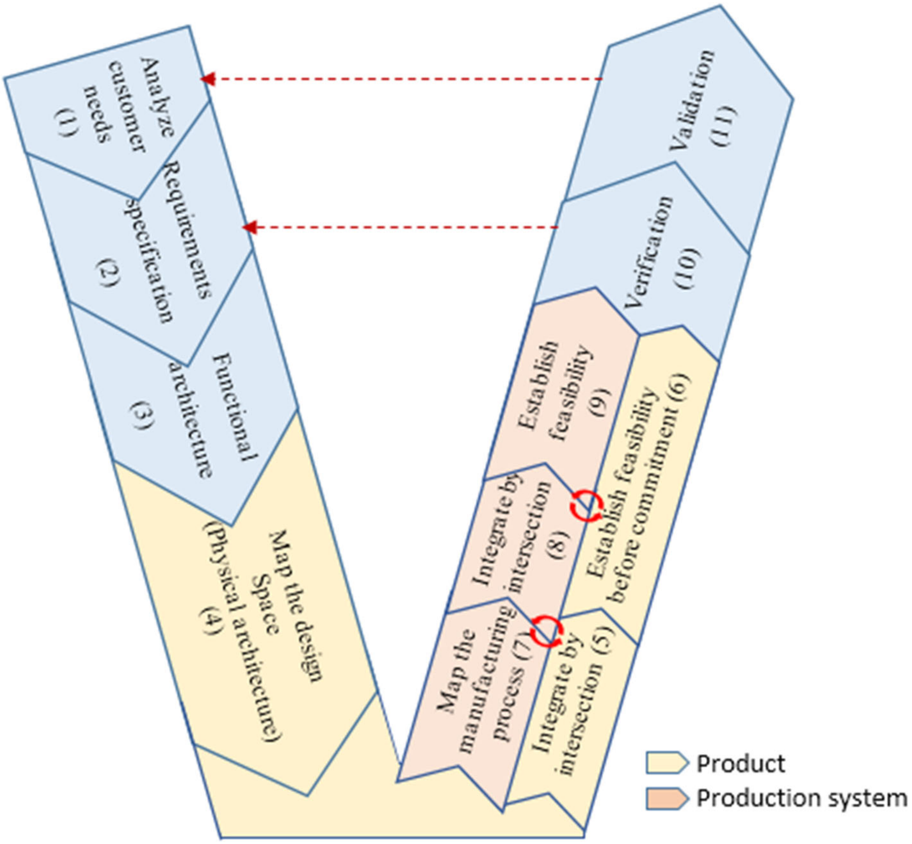


Fig. 4 The development approach based on the system engineering V-cycle

$$R_{yq} = \begin{bmatrix} r_{11} & \cdots & r_{1m} & \cdots & r_{1q} \\ \vdots & \ddots & \vdots & \iddots & \vdots \\ r_{n1} & \cdots & r_{nm} & \cdots & r_{nq} \\ \vdots & \iddots & \vdots & \ddots & \vdots \\ r_{y1} & \cdots & r_{ym} & \cdots & r_{yq} \end{bmatrix} \quad \text{with } r_{ij}\ \varepsilon[1,\ 5]$$

The set of developed solutions was represented by a dependency graph with the help of our first algorithm. In this dependency graph, each node corresponds to a sub-system solution and is characterized by the attributes provided in the R_{yq} while each arc indicates a dependency between two solutions and is defined by the attributes developed in a DSM D_{yy} dependency matrix.

$$D_{yy} = \begin{bmatrix} d_{11} & \cdots & d_{1m} & \cdots & d_{1y} \\ \vdots & \ddots & \vdots & \iddots & \vdots \\ d_{n1} & \cdots & d_{nm} & \cdots & d_{ny} \\ \vdots & \iddots & \vdots & \ddots & \vdots \\ d_{y1} & \cdots & d_{ym} & \cdots & d_{yy} \end{bmatrix} \quad \text{with } d_{ij}\ \varepsilon[1,\ 5]$$

Moreover, each node is characterized by a specific weight (NW) computed by our algorithm using Eq. 1.

$$NW_y = \left|R_{yq} \times VR_q\right| = \left| \begin{bmatrix} r_{11} & \cdots & r_{1m} & \cdots & r_{1q} \\ \vdots & \ddots & \vdots & \iddots & \vdots \\ r_{n1} & \cdots & r_{nm} & \cdots & r_{nq} \\ \vdots & \iddots & \vdots & \ddots & \vdots \\ r_{y1} & \cdots & r_{ym} & \cdots & r_{yq} \end{bmatrix} \times \begin{pmatrix} \varepsilon_1 \\ \vdots \\ \varepsilon_n \\ \vdots \\ \varepsilon_q \end{pmatrix} \right| = \left| \begin{pmatrix} \sum_{i=1}^{q} r_{1i}\varepsilon_i \\ \sum_{i=1}^{q} r_{ni}\varepsilon_i \\ \sum_{i=1}^{q} r_{yi}\varepsilon i \end{pmatrix} \right| \tag{1}$$

By means of this dependency graph, the matrices and the mathematical equations developed in [53], our algorithm can find the possible solutions matching our system, place them in new DMM matrix named G_{ty} and then gradually reduce their number.

$$G_{ty} = \begin{bmatrix} \delta_{11} & \cdots & \delta_{1m} & \cdots & \delta_{1y} \\ \vdots & \ddots & \vdots & \iddots & \vdots \\ \delta_{n1} & \cdots & \delta_{nm} & \cdots & \delta_{ny} \\ \vdots & \iddots & \vdots & \ddots & \vdots \\ \delta_{t1} & \cdots & \delta_{tm} & \cdots & \delta_{ty} \end{bmatrix}$$

The narrowing in the number of solutions is based on the dependency weight GDW and the performance one GNW which is modified by moving from one reduction to another and by adding each time the requirements with higher percentages than a calculated value depending on the number of reductions reached each time. The GDW and the GNW are calculated using data matrices and Eqs. (2 and 3) developed in [53].

$$GNW_t = \left|G_{ty} \times NW_{yp}\right| = \left\| \begin{pmatrix} \sum_{j=1}^{y} \delta_{1j} \sum_{i=1}^{p} r_{ji}\varepsilon_i \\ \sum_{j=1}^{y} \delta_{nj} \sum_{i=1}^{p} r_{ji}\varepsilon_i \\ \sum_{j=1}^{y} \delta_{tj} \sum_{i=1}^{p} r_{ji}\varepsilon i \end{pmatrix} \right\| \tag{2}$$

$$GDW_{tt} = diag\left|G_{ty} \times D_{yy} \times {}^{t}G_{ty}\right| = \left| \begin{pmatrix} \sum_{j=1}^{y} \delta_{1j} \sum_{i=1}^{y} \delta_{1i} d_{ij} \\ \vdots \\ \sum_{j=1}^{y} \delta_{nj} \sum_{i=1}^{y} \delta_{ni} d_{ij} \\ \vdots \\ \sum_{j=1}^{y} \delta_{tj} \sum_{i=1}^{y} \delta_{ti} d_{ij} \end{pmatrix} \right| \tag{3}$$

Our first algorithm stops if we reach a number of solutions inferior to K fixed at the beginning of the algorithm according to the clients' choice or until taking in consideration all the requirements defined at the beginning of the algorithm to calculate the performance weight.

Our algorithm is mainly based on an arborescence graph SG (Fig. 5) which will be read as an entry by it, focusing on the nodes included in the sub-systems level and the set of possible solutions one. Indeed, node 0 represents the global system, nodes 1, 2, 3 and 4 reflect the decomposition in sub-systems where each node constitute a sub-system and the nodes (5, 6), (7, 8, 9), (10, 11) and (12, 13) are the set of possible solutions of the subsystems 1, 2, 3 and 4 respectively. Finally, nodes (14, 15, 16), (16, 17) (18, 19), (20, 21) and (22, 23) stand for the decomposition level of solutions 7, 8, 9, 12 and 13 of the constituents which must be manufactured. The last level is added to the solutions composed of more than one constituent and will be used in the following steps.

The results obtained in the first algorithm are in the form of DMMs matrices as well as an RSSG graph saved in a GraphML file. The subsequent steps in our approach, based on these results, seek to narrow much more the number of the remaining solutions adding constraints related to the production system. In fact, the first resulting DMM matrix named GSM represents the remaining global solutions in terms of their characteristics (GNW and GDW). The second one named RSM represent the remaining sub-systems solutions set and its decomposition to parts appearing under the set of possible solutions level of the previous graph in relation to length, width, height, volume, weight, material parts, industry types, machinability, material availability, parts to fabricate and parts to purchase. The two last columns of our matrix are filled with 0 and 1 while the remaining ones are empty.

The matrix empty grids of the components to be fabricated must be filled later on with the corresponding maximum values including volume, weight, length, width, and height as well as the material type corresponding to each constituent, material availability, industry types which may be used for its production and machinability index in the right grid.

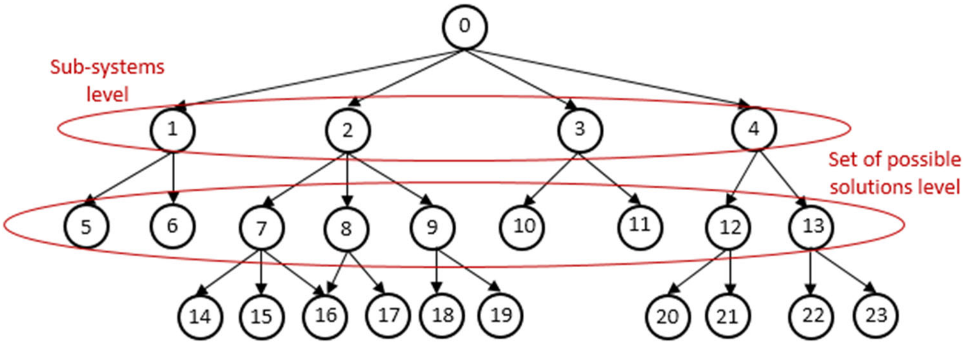


Fig. 5 Arborescence Graph of the set of possible solutions and their decomposition

The second resulting matrix named GSM encompasses the remaining global solutions in accordance with their characteristics which include the global nodes weight and the global dependency ones calculated by the first algorithm [53].

The two resulting matrices attained by the ARNS algorithm and the RSSG dependency graph will be used in the following steps by the AAM and ARPU algorithms. These seek to find all the production systems set of possibilities and to reduce much more the number of the remaining solutions by adding the constraints linked to the production systems.

3.2 Production system development

This phase chiefly aims at creating an environment in which both production engineers and those from other fields collaborate. Consequently, the production system constraints will be introduced in the preliminary design phases to help the system engineer converge towards the best system/system production solution among a set of solutions and reduce, afterwards, the iterative exchange loops, emerging in the late design stages, between designers and production engineers. In this phase, the optimal system solution with the lowest cost and the shortest development time is reached. Indeed, a production error, which is discovered in the preliminary design phases, is relatively less expensive to correct.

The SBCE approach principles are used and implemented in the system engineering V-cycle model. They are converted to a framework suitable for production. The first principle design space of this approach is substitute for a set of production processes. This phase simultaneously evaluates a set of production processes in the first development phase "conceptual design phase" in order to minimize the rework between all possible stakeholders included in the process by adopting filters.

3.2.1 Step 7: Map manufacturing process

In this step, the SysML BDD diagram is firstly exploited to develop the set of machines available in the factory and which are able to meet the need of manufacturing the remaining solutions; taking into account the industry types which will be used for their manufacturing. Thereupon, Gephi, an open source software for network visualization as well as analysis, is employed to implant these machines in an arborescence graph MG (Fig. 6). The nodes first level in the MG graph represents the machine types. Indeed, each node features a specific machine type. The nodes second level shows the set of machines available for each machine type of the preceding node. In this level, each node must be characterized by specific attributes including the maximum weight that can be carried by the machine, the maximum volume, length, width and height that can be processed by each machine as well as the labor cost per second and the processing time per cm^3 for each machine if identified. Moreover, a DMM matrix named PM will be developed to define the raw materials cost that can be used to make the remaining component sets.

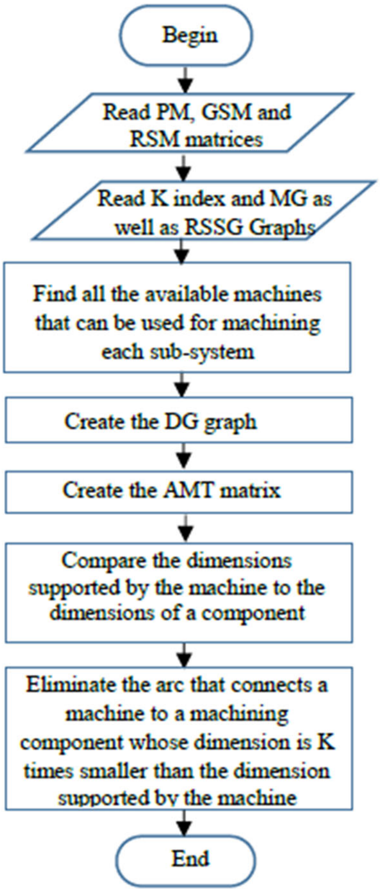
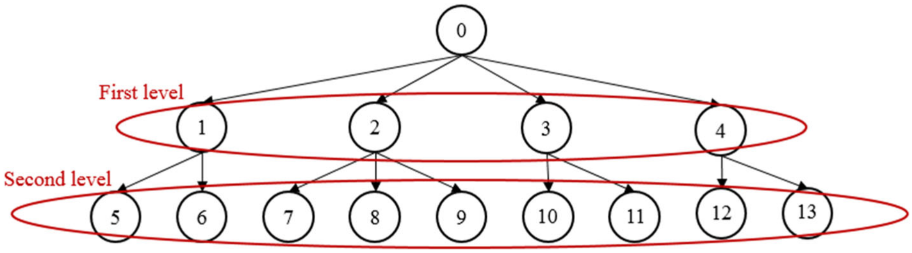


Fig. 7 Flowchart of the Machine Allocation Algorithm MAA

Fig. 6 Arborescence Graph of the available machines in the factory



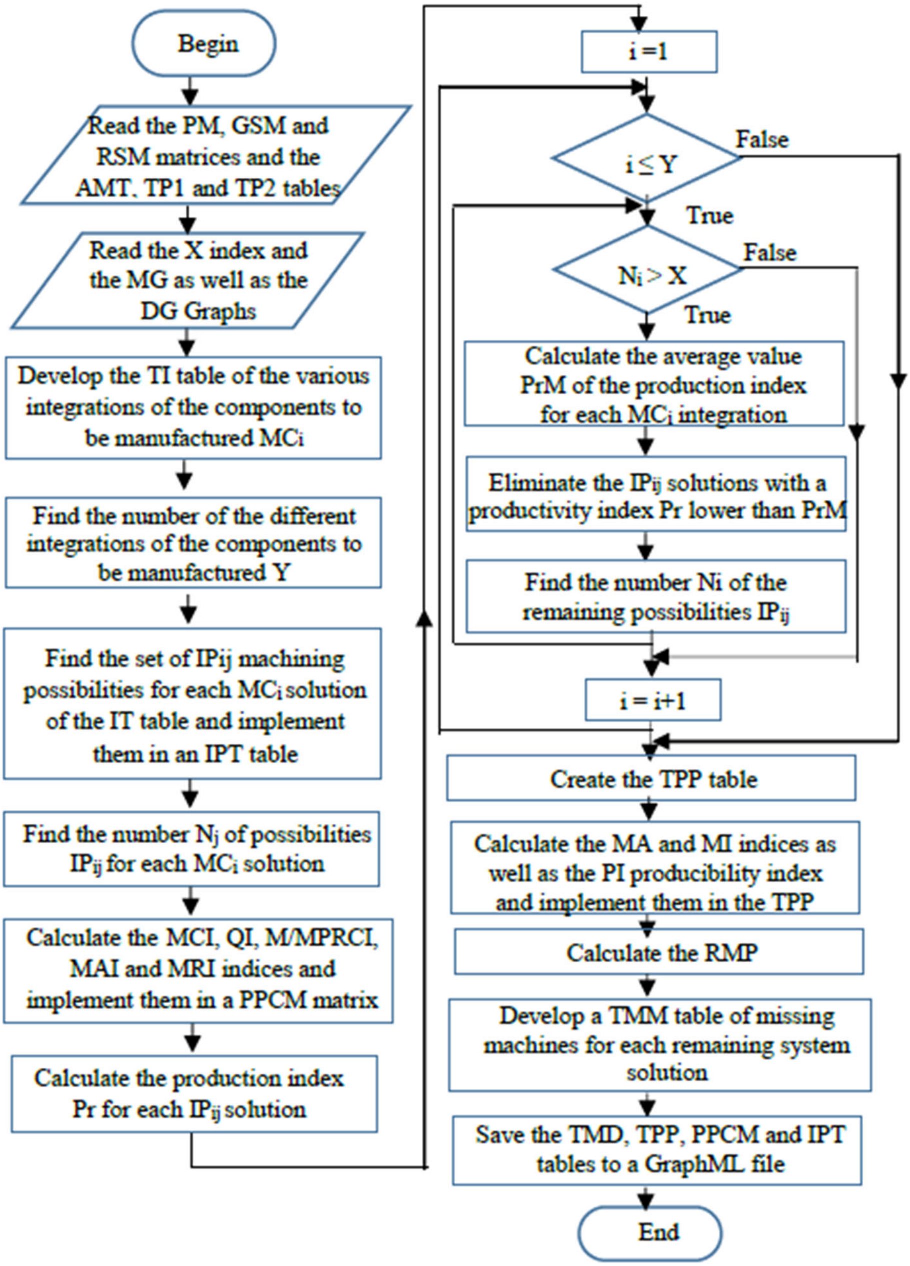


Fig. 8 Flowchart of the PPRA algorithm for reducing the number of machining possibilities IP_{ij}

3.2.2 Steps (8) and (9)

These steps are essentially based on our two algorithms named the Machine Allocation Algorithm (MAA) and the Production Possibilities Reduction Algorithm (PPRA) represented by two flowchart in the Figs. 7 and 8, respectively.

The first algorithm use as entries the MG machines arborescence graph, the RSSG graph, the GSM matrix of the remaining global solutions and the RSM matrix of the remaining subsystem solution. This algorithm aims at determining the components which may be manufactured in a given factory. It also identifies the set of machines available for their production and those missing for the development of the parts which cannot be fabricated in that factory. The set of available machines will be defined in the Available Machine Table (AMT) in terms of a components column in which the part to be manufactured by the machine of the same line is defined as well as empty columns of quality, cost and compatibility which are, afterwards, filled with indices from 1 to 5 by experts .

This table is, then, read by the PPRA algorithm which attempts to narrow the number of possible solutions and the number of machines that can be used to process the remaining parts in order to converge towards the best solution and its most suitable production system.

A new dependency graph DG (Fig. 9), in which

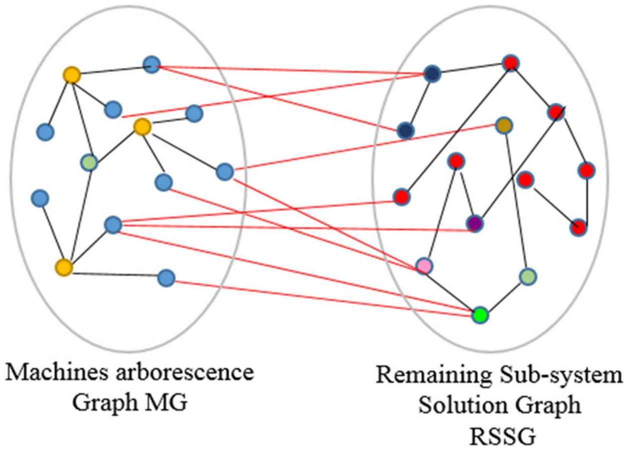


Fig. 9 DG dependency graph relating the subsystem solutions and the available machines

the remaining sub-system solution graph RSSG and the machines graph MG are concatenated by red arcs, is developed by our MAA algorithm. Each new arc in this graph links two nodes where the first one corresponds to a sub-system solution while the second stands for the machines available and which can be utilized for its machining. Each solution node can be related to a set of machine nodes by the means of a red arc in order to identify the set of available machines**.**

Quality, cost and compatibility indices of a specific component machined with a particular machine are defined as attributes in the arc that links them. At this level, the MAA algorithm compares the largest dimensions that can be reached by the machine to those of a component. In fact, if the dimensions of that component are K times smaller than those attained by the machine, the red arc that links them is removed. K is specified at the beginning of our algorithm in terms of user choice.

Afterwards, our PPRA algorithm, based on the remaining red arcs, defines the different possibilities of the set of machines IP_{ij} in a chart named IPT. This set can be used to process each component set which must be machined to reach a global system solution.

These remaining global solutions are obtained from the integration of the subsystem possible solution sets. Some of the resulting global solutions may differ for the components to purchase, but they always remain the same for those to build. Hence, the different integrations between the sub-system solution sets of the components to manufacture (MC_i) must first and foremost be identified with the help of our algorithm and implemented in a IT table (the different Integrations of the components to fabricate Table). These integrations are derived from the global solutions located in the GSM matrix and will be used later on in the following steps. The number of these possibilities is implemented in a Y variable. This step, consequently, results in a set of production possibilities NG_i for each global solution (MC_i).

Then, for each processing possibility IPij, our algorithm calculates the MCI Machining Cost Index, the QI Quality Index, the M/MPRCI Material/ Manufacturing Process Risk Compatibility Index, the MAI Machine Availability Index and the MRI Machine Reuse Index.

These indices are implemented in a DMM matrix named PPCM (Production Possibilities/ Characteristics Matrix) which presents the machining global solutions identifiers in terms of their features.

At this level, the PPRA algorithm calculates a Pr Production Index applying equation 4 which uses the PPCM matrix and the TP1 table. This latter introduces the previously-mentioned indices importance percentages, defined using the Analytical Hierarchy Process (AHP). Indeed, the AHP theory aims at obtaining priority scales through a pair comparison depending on experts' judgments [54].

$$\Pr_{i} = \sum_{j=1}^{4} PPCM_{ij} \times TP_j \tag{4}$$

The Pr calculated value of each IP_{ij} solution is implemented in a new column in the PPCM matrix and used to narrow the number of the production possibilities set NG_i of each MC_i solution. This reduction is achieved via calculating, each time, the APr Average value of the remaining solutions Production index using equation 5.

$$A\Pr = \Pr_{\min} + \left(\frac{\Pr_{\max} - \Pr_{\min}}{2}\right) \tag{5}$$

This narrowing phase stops reaching a number of remaining manufacturing solutions for each MC_i solution inferior to X which is fixed in our algorithm according to the users' choice.

A TPP table is, ultimately, created using our PPRA algorithm to define the production process possibilities set of each SR remaining system solution. This table also defines the possibilities set of the system/production system and their characteristics namely the Pr index calculated in the previous step, the MA Material Availability Index, the MI Machinability Index and the CI parts family Compatibility Index. These indices range from 0 to 1. Both the MA and the MI are calculated with the help of our algorithm based on the RSM table values. Moreover, CI corresponds to the GDW (Global Dependency Weight), calculated in the first phases. Furthermore, a producibility index can be calculated in order to be able to compare the remaining solutions and, hereafter, help the system engineer choose the optimal mechatronic system solution and the best corresponding production system simultaneously.

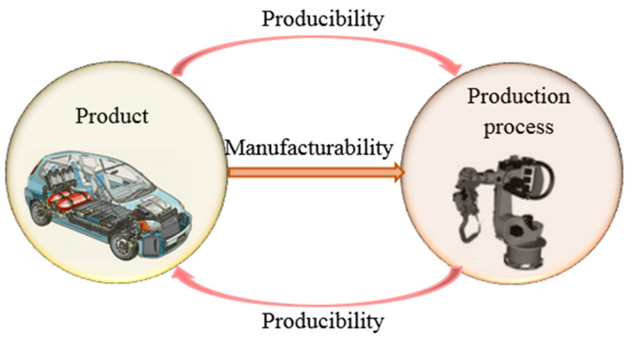


Fig. 10 Producibility and manufacturability contexts

Producibility is defined as a measure used to relatively ease the development of a specific product in an effective and robust way with the highest quality and the lowest cost. To define this term many focus on the ease of components manufacturing [55], while others include an extremely global perspective of how the system is produced [56]. The term "manufacturability" is often used to define "producibility" even though they are alike in numerous cases. Yet, producibility can be distinguished by one aspect as illustrated in Fig. 10. It is, indeed, closely linked to the product functions, characteristics and performances while production optimization rather than product function and characteristics is highlighted in the context of traditional manufacturability or Design For Manufacturing (DFM). This can be explained by the fact that the maturity of product and process technology in, for example, automotive industry is higher. In aerospace industry, however, product performance is necessary and considerably related to the materials as well as process technology. The term producibility is hence preferred (Fig. 10).

The choice of factors used to calculate the producibility index can be based on experts opinions, process type whether unique or new as well as strengths and weaknesses of a specific organization, historical information and technologies. Moreover, as the problems number and the problem importance change within the product development phases, the factors' weight is modified all along the design process increasing or decreasing. An example of some producibility factors and their corresponding weight in two different development phases is given in Table 2.

Since our approach focuses only on the conceptual design phase without reaching the detailed design phase, we concentrate on the first column of the table above in order to calculate the producibility index. At this point, our algorithm calculates the producibility value (PI) for each IPij solution, using equation 6 based on both TPP and TP2 tables. In the TP2 table, read by our algorithm, the importance percentages of the Pr, DM, IU and IC characteristics are defined by the means of the Analytical Hierarchy Process (AHP).

Table 2 The influencing factor of the weighted producibility

	The influencing factor of the weighted producibility	
	Conceptual design phase	Detailed design phase
Manufacturing process selection	5	4
Material availability	4	4
Machinability	3	3
Part family compatibility	3	2
Tolerances and surface finish	*	5
Geometric feature complexity	*	4
Tooling	*	3
Design for assembly	*	5
Drawing specifications	*	4

$$PI_i = \sum_{j=1}^{4} CMI_{ij} * CP_j \qquad (6)$$

The PI value calculated for each solution IPij is implemented in a new "Prd" column in the TPP table. Then, it is converted to an index from 1 to 5 in another "PrdI" column in order to be sent to system engineers who are responsible for selecting the best solution and its most convenient production system.

3.2.3 Steps 10: Verification step

In this stage, system engineers analyze the results obtained from the previous steps and then select the optimal solution.

4 Case study

In this respect, the Electronic Throttle Body (ETB) automotive domain can be considered as a valuable case study on which our methodology is applied. When it was first invented, the Throttle Body (TB) was all about a mechanical device attached to the accelerator pedal by means of a cable. Yet, it has currently evolved into a mechatronic device directly related to the Electronic Control Unit (ECU) to become an Electronic Throttle Body (ETB). The device mainly controls the airflow in the internal combustion engine and consequently enhances vehicle emissions, improves drivability and controls the combustion vehicle torque seeing that it is proportionally associated with the airflow in the cylinders [57, 58].

Table 3 Sets for each subsystem

Subsystem	Label	Set of possibility
Body	S11	One bloc, co-molded, bi-plastic
	S12	One bloc, molded, plastic
	S13	One bloc, molded, metal
	S14	Two-bloc, molded,metal
	S15	Three-bloc, molded, plastic
Adapt Mechanical Energy	S21	Plastic gears molded
	S22	Metal gears
	S23	Plastic gears over molded
	S24	Metal connected
	S25	Plastic connected
Regulate airflow system	S31	Metal regulate airflow system
	S32	Metal plate shaft and plastic throttle plate
Transfer Energy	S41	DC motor
	S42	Stepper motor
Measure opening	S51	Double track potentiometer
	S52	Simple potentiometer
Controller	S61	PI Controller
	S62	PID Controller
Failsafe system	S71	One spring
	S72	Two springs

Table 4 The remaining sub-system solutions

Subsystem	Label	Set of possibility
Body	S11	One bloc, co-molded, bi-plastic
	S12	One bloc, molded, plastic
Adapt Mechanical Energy	S23	Plastic gears over molded
Regulate airflow system	S32	Metal plate shaft and plastic throttle plate
Transfer Energy	S41	DC motor
	S42	Stepper motor
Measure opening	S51	Double track potentiometer
Controller	S61	PI Controller
	S62	PID Controller
Failsafe system	S72	Two springs

4.1 Steps (1), (2), (3), (4), (5) and (6)

These phases correspond to the main purpose of the first paper [53] in which we developed a new approach to help implement the SBCE approach for the development of complex systems in the industrial domain. In [53], the SBCE principles are used to develop the physical architecture after focusing on understanding clients' requirements and developing the functional architecture. Hence, a set of solutions for each sub-system is developed and defined in the Table 3.

A set of possible global system solutions equal to 480 were obtained and then reduced to 6 solutions with the help of our algorithm which used the mathematical equations and matrices developed in [53]. Table 4 represents the remaining sub-system solutions while 6 represents the remaining global system solutions. Both are going to be utilized in the following steps.

Our First algorithm included data matrices and an arborescence graph (SG) as entries. The graph defined the subsystems in the first level, the set of possible solutions for each sub-system in the second level and an additional last level used only to develop a resulting matrix RSM will also be utilized by our second algorithm during the following phases (Fig. 11).

Our first algorithm resulting matrices are read by Gephi. The first resulting matrix RSM is featured in the Table 5.

As shown in the following figure, this matrix will be read by our second algorithm after filling the empty grids with

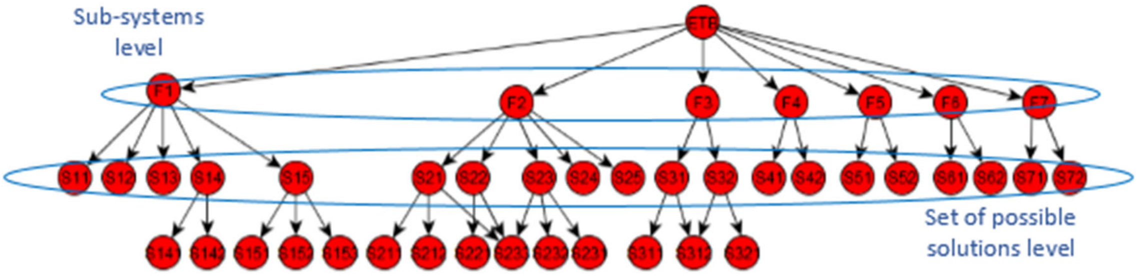


Fig. 11 Arborescence Graph of the set of the sub-system possible solutions and their decomposition

Table 5 First algorithm resulting matrix of the remaining sub-system solutions

Id	Label	Label2	Components	Materials type	Materials	Machining	Machinability	Material availability	Length	Width	Weight	Height	Volume	Number	Purchasing	Manufacturing
1	S11	S11	One bloc, co-molded, bi-plastic body												0	1
2	S12	S12	One bloc, molded, plastic												0	1
3	S23	S231	Plastic gearwell over molded												0	1
4	S23	S232	Plastic gearwell molded												0	1
5	S23	S233	Metal pinion												0	1
6	S32	S312	Metal plate shaft												0	1
7	S32	S321	Plastic throttle plate												0	1
8	S41	S41	Dc motor												1	0
9	S42	S42	Stepper motor												1	0
10	S51	S51	Double track potentiometer												1	0
11	S61	S61	PI controller												1	0
12	S62	S62	PID controller												1	0
13	S72	S72	Two springs												1	0

Table 6 Caracteristics of the remaining sub-system solutions

Id	Label	Label2	Components	Materials type	Materials	Machining	Machinability	Material availability	Length	Width	Weight	Height	Volume	Number	Purchasing	Manufacturing
1	S11	S11	One bloc, co-molded, bi-plastic body	Plastic	0.5 glass-filled nylon, 0.5 PPS	Co-molding	5.0	5.0	120.0	75.0	490.0	110.0	350.0	1000.0	0	1
2	S12	S12	One bloc, molded, plastic	Plastic	PPS	[molding machines][4axix machining center]	5.0	3.0	120.0	75.0	490.0	110.0	350.0	1000.0	0	1
3	S23	S231	Plastic gearwell over molded	Plastic	PPS	Over molding machines	5.0	3.0	42.5	42.5	22.0	11.0	15.59	1000.0	0	1
4	S23	S232	Plastic gearwell molded	Plastic	PPS	Molding machines	5.0	5.0	62.5	62.5	128.0	30.0	92	1000.0	0	1
5	S23	S233	Metal pinion	Metal	raw steel	Sintering machines	5.0	4.0	20.0	20.0	35.0	14.0	4.396	1000.0	0	1
6	S32	S312	Metal plate shaft	Metal	raw aluminum	CNC turning machine	5.0	5.0	100.0	15.0	46.0	15.0	17.662	1000.0	0	1
7	S32	S321	Plastic throttle plate	Plastic	PEI	[Stamping press machine, molding machines	5.0	3.0	50.0	50.0	22.0	8.0	15.7	1000.0	0	1
8	S41	S41	Dc motor	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		1	0
9	S42	S42	Stepper motor	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		1	0
10	S51	S51	Double track potentiometer	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		1	0
11	S61	S61	PI controller	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		1	0
12	S62	S62	PID controller	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		1	0
13	S72	S72	Two springs	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		1	0

Table 7 The Remaining Global System Solution and its caracteristics

Id	Label	GNW	GDW	GW
1	[‘S11’, ‘S23’, ‘S32’,’ S41’, S51’, ‘S61’, S72’]	0.999331	0.977778	1.977108
2	[‘S11’, ‘S23’, ‘S32’,’ S41’, S51’, ‘S62’, S72’]	0.973934	0.977778	1.951712
3	[‘S11’, ‘S23’, ‘S32’,’ S42’, S51’, ‘S61’, S72’]	0.944595	0.955556	1.900151
4	[‘S12’, ‘S23’, ‘S32’,’ S41’, S51’, ‘S61’, S72’]	0.996616	0.955556	1.952172
5	[‘S12’, ‘S23’, ‘S32’,’ S41’, S51’, ‘S62’, S72’]	0.971219	0.955556	1.926775
6	[‘S12’, ‘S23’, ‘S32’,’ S42’, S51’, ‘S61’, S72’]	0.941881	0.977778	1.919659

their corresponding values in the lines for components to fabricate (Table 6).

The second resulting matrix of our first algorithm GSM, which defines the remaining global solutions in accordance with their features such as the global nodes weight GNW, the global dependency weight GDW and the global weight of each remaining system solution, will be read as an entry by our second algorithm as indicated in the following chart (Table 7).

4.2 Production system development

The Block Definition Diagram (BDD) is firstly used in order to define all the types of machines which are necessary for the production of the remaining sub-systems solutions set. Indeed, the remaining sub-systems solutions components, the machining types necessary for their production and the machines required for a production process to develop a final product are taken into consideration so as to developed this BDD diagram. This diagram is shown in Fig. 12.

4.2.1 Step7: Map manufacturing process

As shown in Fig. 13, the BDD SysML diagram is used in order to identify the set of machines available in the factory and able to meet our needs regarding the remaining solutions processing, takin into account the BDD diagram introduced in Fig. 10.

In our case study, we need a plastic injection-molding machine, a metal injection-molding machine, a co-molding machine, a stamping press machine, a sintering machine, a 4-axis machining center, a CNC rotating machine and an over-molding machine to produce the remaining subsystems solutions components.

As indicated in the Fig. 14 below, all these machines are implanted in an arborescence graph MG using Gephi to be read, afterwards, by the MAA algorithm.

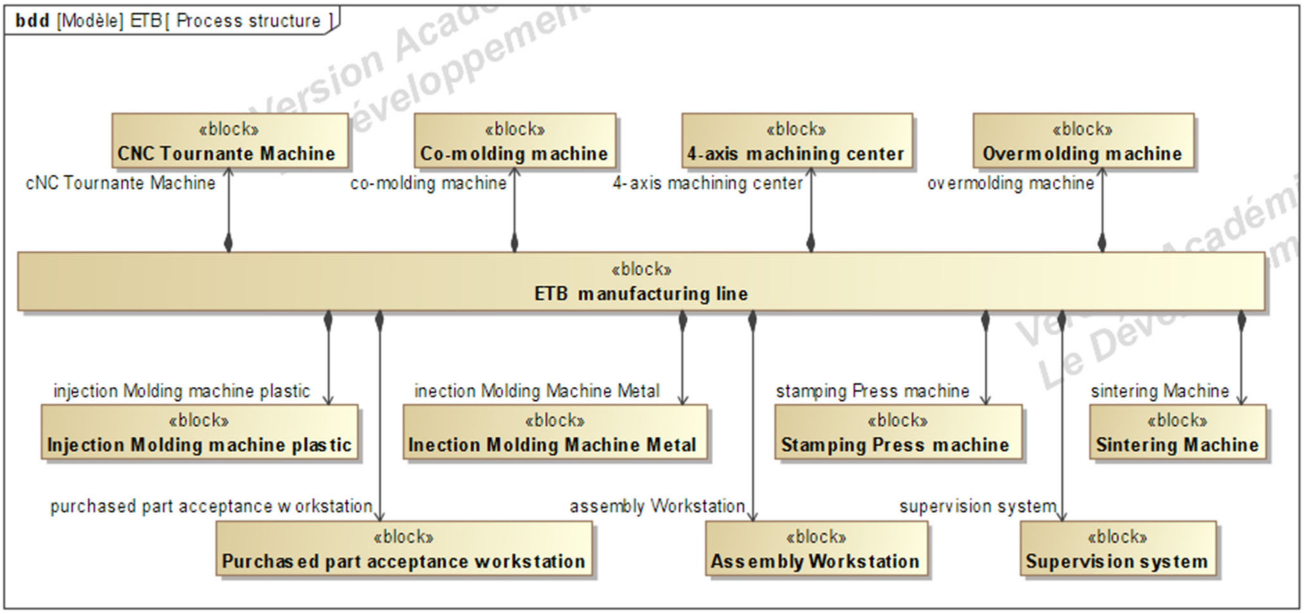


Fig. 12 The ETB production process structure

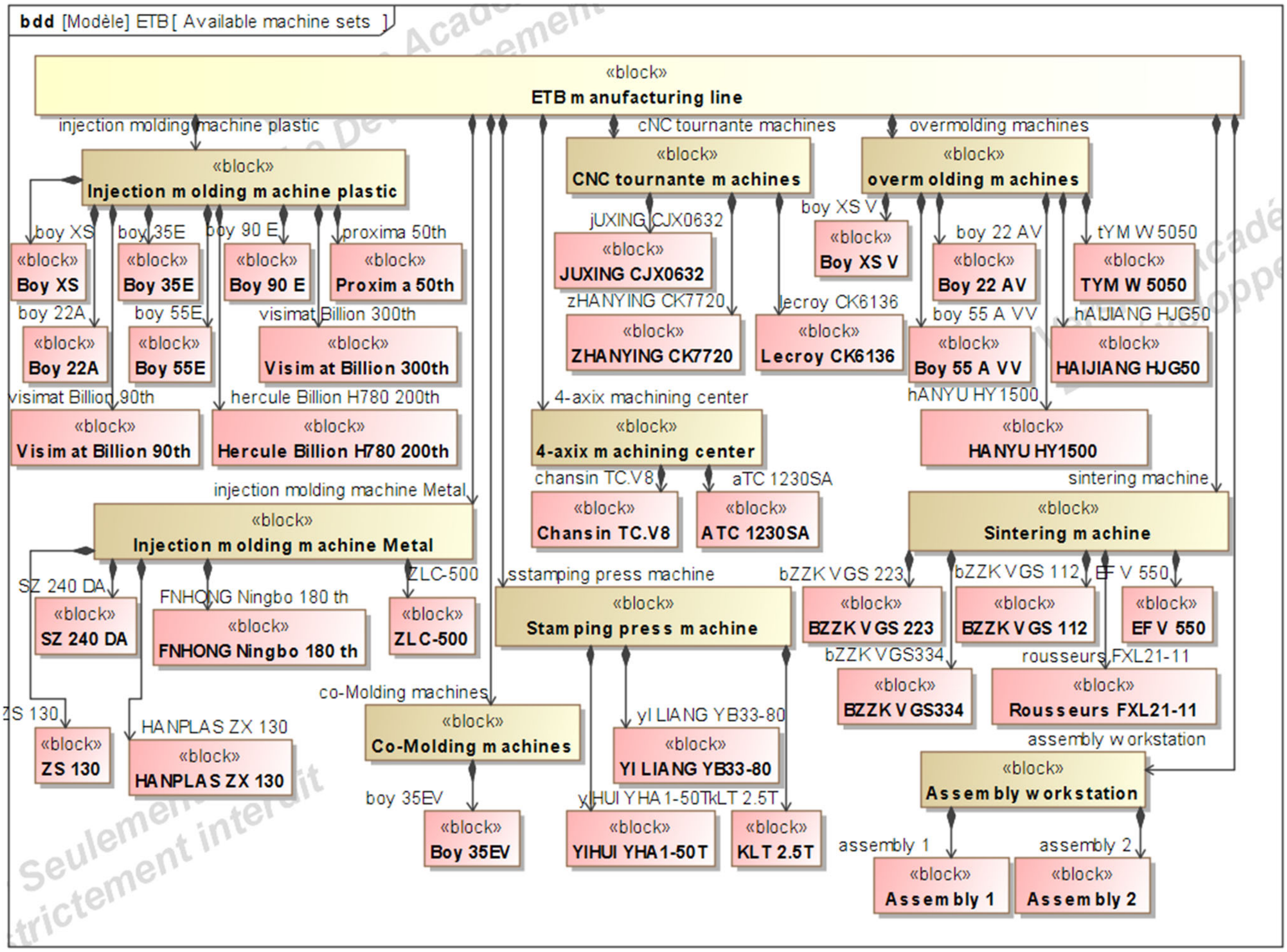


Fig. 13 The SysML BDD Diagram of available machines

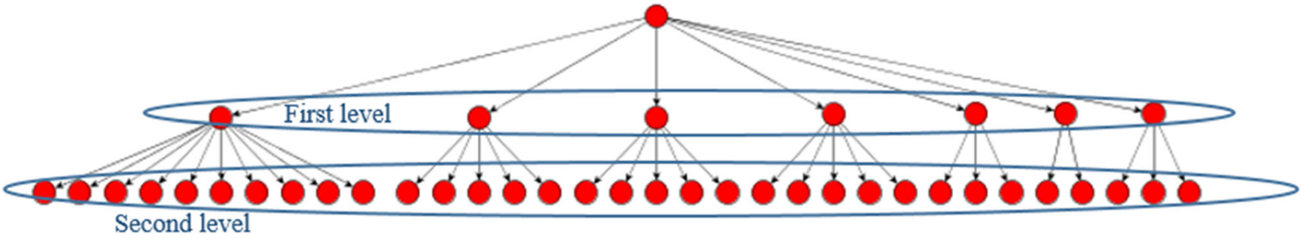


Fig. 14 Arborescence Graph of the available machines in the factory

Each node in the first nodes level presents a specific type of machines including the plastic injection machines, the metal injection machines, the over-molding machines, the stamping machines and the sintering machines. The second level includes the set of available machines. Indeed, each node corresponds to the machine belonging to the type of machine of the preceding node characterized by attributes such as the maximal weight withstood by the machine, the maximum length, width and height that can be processed by each machine and the labor cost index per second of each machine. Moreover, a chart including the cost of the raw materials which can be used for the manufacturing of the set of remaining components is developed using Gephi (Table 8).

This chart will be used later on to calculate the approximate cost of system solution raw materials.

4.2.2 Steps 8 and 9: Integrate by intersection and establish feasibility

The MAA algorithm first identifies the components that can be manufactured in the factory as well as the missing

Table 8 Raw Material Price (PM)

Id	Label	Materials type	Price in g
0	PPS	Plastic	0.0057
1	Glass-filled nylon	Plastic	0.0015
2	Raw aluminum	Metal	0.0018
3	PEI	Plastic	0.018
4	Powder aluminum	Metal	0.00168
5	Raw steel	Metal	0.000674

machines for the processing of components that cannot be manufactured within this factory as shown in the Table 9.

The dependency graph displayed by this algorithm (Fig. 15) includes the remaining sub-system solutions components of the ARNS algorithm and their remaining integrations defining the remaining global system solutions.

This graph red nodes represent the components to be purchased. The nodes with the same color constitute the components to be fabricated belonging to the same solution. The remaining nodes represent the other sub-system solutions to be fabricated which are made up of only one part.

The second MG graph shown by the MAA algorithm accounts for the set of machines available in the factory.

The yellow nodes included in this graph (Fig. 16) represent the first level of the machines arborescence graph first level (Fig. 14) made by Gephi and read by the MAA algorithm while the blue nodes constitute the graph second level.

The third graph DG (Fig. 17) submitted by our algorithm is a graph resulting from its processing.

This graph results from a concatenation of two preceding graphs MG and RSSG through red arcs which link each component to be fabricated to the machines that can be used for its manufacturing. The machines which cannot be utilized for the fabrication of components are related to no arc. Therefore, the number of available machines is narrowed. A second reduction of the number of machines which can be used for the manufacturing of each part is realized through comparing the dimensions which can be carried by the machine to component dimensions. If they are K times smaller than those withstood by the machine , the red arc connecting them will be deleted as shown in the Fig. 18. In our case study K is fixed as equal to 5.

The graph in the Fig. 18 is saved in a GraphML file so that it can be translated into a data table as shown in the Table 9.

The integration dots are attributed to the read arcs which must be filled with the experts help with indices from 1 to 5 (5 refers to the best feature) as indicated in the Table 10.

This MAT table is read by the PPRA algorithm aiming at narrowing the number of machines and converging towords the best production line for each system solution. As for the

Table 9 Data table of the DG graph resulting from the MAA algorithm

Id	Solution	Label1	Machine type	Machine 1	Machine 2	Quality	Cost	Compatibility
36	2	S23-M22	Plastic gearwell over molded	Boy 55 A VV		?	?	?
37	2	S23-M23	Plastic gearwell over molded	HAIJIANG HJG50		?	?	?
38	3	S23-M14	Plastic gearwell molded	Visimat billion 90th		?	?	?
39	4	S23-M41	Metal pinion	Rousseurs FXL 21–11		?	?	?
40	4	S23-M43	Metal pinion	BZZK VGS 112		?	?	?
41	5	S32-M71	Metal plate shaft	JUXING CJX0632		?	?	?
42	5	S32-M72	Metal plate shaft	ZHANYING CK7720		?	?	?
43	6	S32-M14	Plastic throttle plate	Visimat billion 90th		?	?	?
44	6	S32-M15	Plastic throttle plate	Proxima 50th		?	?	?
45	1	S12-M13	One bloc, molded, plastic	Hercule Billion H780 200th		?	?	?
46	1	S12-M91	One bloc, molded, plastic	Disamatic C3-150		?	?	?
47	1	S12-M62	One bloc, molded, plastic		ATC 1230SA	?	?	?

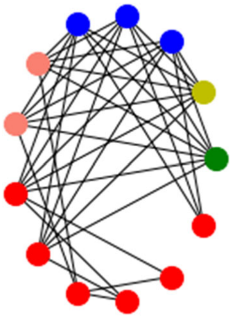


Fig. 15 Dependancy Garph of the remaining sub-system solutions

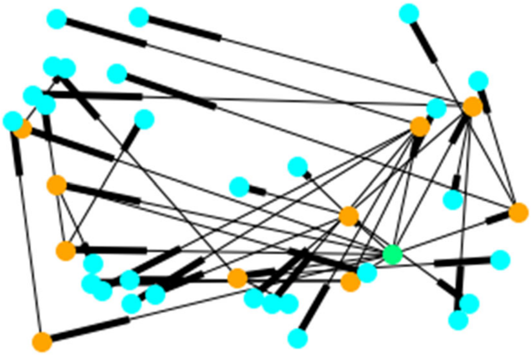


Fig. 16 Graph of the available machines in the factory

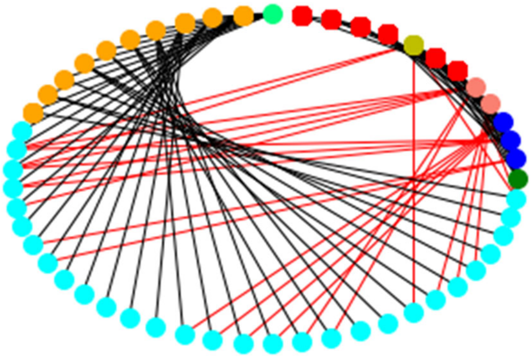


Fig. 17 Graph of the identification of the available machines sets to process each sub-system solutions

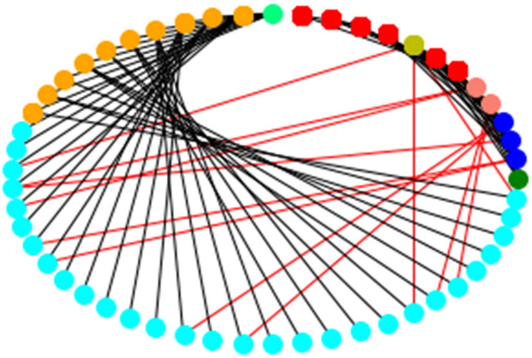


Fig. 18 DG Graph after the narrowing of the available machine numbers

Table 10 AMT Data table of the DG graph filled according to experts

Id	Solution	Label1	Machine type	Machine 1	Machine 2	Quality	Cost	Compatibility
36	2	S23-M22	Plastic gearwell over molded	Boy 55 A VV		5	4	4
37	2	S23-M23	Plastic gearwell over molded	HAIJIANG HJG50		1	4	3
38	3	S23-M14	Plastic gearwell molded	Visimat billion 90th		5	3	4
39	4	S23-M41	Metal pinion	Rousseurs FXL 21–11		2	5	3
40	4	S23-M43	Metal pinion	BZZK VGS 112		5	3	5
41	5	S32-M71	Metal plate shaft	JUXING CJX0632		4	3	4
42	5	S32-M72	Metal plate shaft	ZHANYING CK7720		2	3	4
43	6	S32-M14	Plastic throttle plate	Visimat billion 90th		3	1	3
44	6	S32-M15	Plastic throttle plate	Proxima 50th		4	3	4
45	1	S12-M13	One bloc, molded, plastic	Hercule Billion H780 200th		4	3	4
46	1	S12-M91	One bloc, molded, plastic	Disamatic C3-150		1	5	2
47	1	S12-M62	One bloc, molded, plastic		ATC 1230SA	3	3	5

Table 11 The remaining integration of the sub-system solutions to be manufactured

I	MC_i
1	[‘S11’, ‘S23’, ‘S32’]
2	[‘S12’, ‘S23’, ‘S32’]

Table 12 The key value indicators

Alternatives	Results	
Machine availability	23.9%	🟩
Compatibility	22.4%	🟩
Quality	19.6%	🟩
Cost	18.5%	🟩
Reuse	15.3%	🟩

remaining solutions, we notice that some of the system solutions vary only for the parts to be purchased; but look alike in the development phases of their production line. Consequently, the various integrations of the remaining subsystems solutions to be manufactured MCi are drawn by the PPRA algorithm in order to reduce the processing time. In our case study, only two different integrations, among the 6 remaining system solutions, between the sub-systems solutions to be manufactured are detected as mentioned in the following chart (Table 11).

At this phase, The PPRA algorithm finds 16 production system possibilities for the MC_1 solution components processing and 32 ones for MC_2 solution taking into consideration the DG dependency Graph. All these solutions are implemented in an IPT chart.

Then, the IPT and AMT charts as well as the DG graph are used by our algorithm in order to calculate the MCI, QI, M\MPRCI, MAI and MRI indices for each IP_{ij} solution. These indices are implemented in a DMM matrix (named PPCM) which is used to determine the Pr production index for each solution applying Eq. (1) and using the TP1 table represented in the Tables 12, 13.

Afterwards, the set of possible solutions number for each MC_i is narrowed by our algorithm basing on the production index. In order for this to happen, our algorithm calculates, each time, a production index average value of the remaining solutions and eliminates the solutions with a production index value inferior to this calculated average value till reaching a number of remaining solutions inferior or equal to X fixed according to the users’ choice. In our case study, we choose an X value equal to 5. As shown in the Table 14, our algorithm narrows the number of the production system possibilities from 48 to 5 (3 possibilities for the MC1 solution an 2 for MC2).

As mentioned above, this table displays the MC1 and MC2 remaining production systems. Taking into account the results shown in this table, a recent chart, named TPP, is created using the PPRA algorithm in order to define the production possibilities for the 6 remaining solutions set SR of the ARNS algorithm.

Each system\production system solution is characterised by Pr, MAI, MI and CI indices as well as a system solution performance index GNW extracted from the GSM table. At this stage, a producibility index (PI) is calculated for each system\production system solution using Eq. 3 then transformed into a PrdI index ranging from 1 to 5, in order to help system engineers to select the most sotable solution. The Prd and PrdI values are put in two new columns in the TPP table as shown in the Table 15.

To calculate the Prd index, the PPRA algorithm uses, aside from the 4 indices Pr, MAI, MI and CI, the TP2 table as indicated in the Table 16.

All the remaining components characteristics and the remaining system solutions are saved in the 17 and 18 tables in the form of GrapML files (Tables 17, 18).

The chart 17 helps to determine the components that can be produced in the factory with the word “yes” provided in the ability column and “no” otherwise. It also allows us to identify the cost of the raw materials used to make the overall number of components in the “RMPFTNP” column and all the machines which can be used to fabricate each part in the “machine n” columns, in which n represents the number of processing types which will be applied to make the desired parts.

In addition, the 18 chart displays the remaining global system solutions appearing in the GSM table adding the possibility, or not, of manufacturing a specific component. On the one hand, if all the sub-system solutions made up of a global system solution can be manufactured in the factory, the chart indicates “PIOC” in the manufacturing column. On the other hand, if one or several parts cannot be manufactured in the factory, the sentence “lack n machines to make S_{ij} appears giving the number of the missing machines “n” and the components S_{ij} which cannot be manufactured. Furthermore, each global solution will be characterized by the raw material cost which will be utilized to manufacture the overall number of the system solution in the “RMP” column, the Global dependency weight GDW and the performance weight GNW.

These results will be sent to system engineers who will choose the best system solution and its most convenient production system.

It is worth noting that the solutions which cannot be manufactured due to the lack of some machines for the manufacturing of some components mustn’t be automatically

Table 13 Production possibilities/characteristics matrix PPCM

Id	MC	S11	S12	S231	S232	S233	S312	S321	Machine availability	Compatibility	Quality	costs	reuse	PrI
1	1	No available machine		HAIJING HJG50	Visimat billion 90th	Rousseurs FXL21-11	JUXING CJX0632	Visimat billion 90th	4.16667	3.4	3.0	3.2	4.167	3.577
2	1	No available machine		HAIJING HJG50	Visimat billion 90th	Rousseurs FXL21-11	JUXING CJX0632	Proxima 50th	4.16667	3.6	3.2	3.6	5.0	3.864
3	1	No available machine		HAIJING HJG50	Visimat billion 90th	Rousseurs FXL21-11	ZHANYING CK7720	Visimat billion 90th	4.16667	3.4	3.6	3.2	4.167	3.503
4	1	No available machine		HAIJING HJG50	Visimat billion 90th	Rousseurs FXL21-11	ZHANYING CK7720	Proxima 50th	4.16667	3.6	3.2	3.6	5.0	3.790
5	1	No available machine		HAIJING HJG50	Visimat billion 90th	BZZK VGS112	JUXING CJX0632	Visimat billion 90th	4.16667	3.8	3.6	2.8	4.167	3.699
6	1	No available machine		HAIJING HJG50	Visimat billion 90th	BZZK VGS112	JUXING CJX0632	Proxima 50th	4.16667	4.0	3.8	3.2	5.0	3.987
7	1	No available machine		HAIJING HJG50	Visimat billion 90th	BZZK VGS112	ZHANYING CK7720	Visimat billion 90th	4.16667	3.8	3.2	2.8	4.167	3.625
8	1	No available machine		HAIJING HJG50	Visimat billion 90th	BZZK VGS112	ZHANYING CK7720	Proxima 50th	4.16667	4.0	3.4	3.2	5.0	3.913
9	1	No available machine		Boy 55 A VV	Visimat billion 90th	Rousseurs FXL21-11	JUXING CJX0632	Visimat billion 90th	4.16667	3.6	3.2	3.2	4.167	3.769
10	1	No available machine		Boy 55 A VV	Visimat billion 90th	Rousseurs FXL21-11	JUXING CJX0632	Proxima 50th	4.16667	3.8	3.4	3.6	5.0	3.057
11	1	No available machine		Boy 55 A VV	Visimat billion 90th	Rousseurs FXL21-11	ZHANYING CK7720	Visimat billion 90th	4.16667	3.6	3.4	3.2	4.167	3.695
12	1	No available machine		Boy 55 A VV	Visimat billion 90th	Rousseurs FXL21-11	ZHANYING CK7720	Proxima 50th	4.16667	3.8	3.6	3.6	5.0	3.983

Table 13 (continued)

Id	MC	S11	S12	S231	S232	S233	S312	S321	Machine availability	Compatibility	Quality	costs	reuse	PrI
13	1	No available machine		Boy 55 A VV	Visimat billion 90th	BZZK VGS112	JUXING CJX0632	Visimat billion 90th	4.16667	4.0	3.4	2.8	4.167	3.892
14	1	No available machine		Boy 55 A VV	Visimat billion 90th	BZZK VGS 112	JUXING CJX0632	Proxima 50th	4.16667	4.2	3.6	3.2	5.0	4.179
15	1	No available machine		Boy 55 A VV	Visimat billion 90th	BZZK VGS112	ZHANYING CK7720	Visimat billion 90th	4.16667	4.0	4.0	2.8	4.167	3.818
16	1	No available machine		Boy 55 A VV	Visimat billion 90th	BZZK VGS 112	ZHANYING CK7720	Proxima 50th	4.16667	4.2	4.2	3.2	5.0	4.106
17	2		Disamatic C3-150, ATC 1230SA	HAIJING HJG50	Visimat billion 90th	Rousseurs FXL21-11	JUXING CJX0632	Visimat billion 90th	5.0	3.428571	2.714286	3.428	4.285	3.792
18	2		Disamatic C3-150, ATC 1230SA	HAIJING HJG50	Visimat billion 90th	Rousseurs FXL21-11	JUXING CJX0632	Proxima 50th	5.0	3.571429	2.857143	3.714	5.0	4.016
19	2		Disamatic C3-150, ATC 1230SA	HAIJING HJG50	Visimat billion 90th	Rousseurs FXL21-11	ZHANYING CK7720	Visimat billion 90th	5.0	3.428571	2.428571	3.428	4.285	3.74
20	2		Disamatic C3-150, ATC 1230SA	HAIJING HJG50	Visimat billion 90th	Rousseurs FXL21-11	ZHANYING CK7720	Proxima 50th	5.0	3.571429	2.571429	3.142	5.0	3.963
21	2		Disamatic C3-150, ATC 1230SA	HAIJING HJG50	Visimat billion 90th	BZZK VGS112	JUXING CJX0632	Visimat billion 90th	5.0	3.714286	3.142857	3.428	4.285	3.880
22	2		Disamatic C3-150, ATC 1230SA	HAIJING HJG50	Visimat billion 90th	BZZK VGS112	JUXING CJX0632	Proxima 50th	5.0	3.857143	3.285714	3.428	5.0	4.103

Table 13 (continued)

Id	MC	S11	S12	S231	S232	S233	S312	S321	Machine availability	Compatibility	Quality	costs	reuse	PrI
23	2		Disamatic C3-150, ATC 1230SA	HAIJING HJG50	Visimat billion 90th	BZZK VGS112	ZHANYING CK7720	Visimat billion 90th	5.0	3.714286	2.857143	3.142	4.285	3.827
24	2		Disamatic C3-150, ATC 1230SA	HAIJING HJG50	Visimat billion 90th	BZZK VGS112	ZHANYING CK7720	Proxima 50th	5.0	3.857143	3.0	3.428	5.0	4.051
25	2		Disamatic C3-150, ATC 1230SA	Boy 55 A VV	Visimat billion 90th	Rousseurs FXL21-11	JUXING CJX0632	Visimat billion 90th	5.0	3.571429	3.285714	3.428	4.285	3.930
26	2		Disamatic C3-150, ATC 1230SA	Boy 55 A VV	Visimat billion 90th	Rousseurs FXL21-11	JUXING CJX0632	Proxima 50th	5.0	3.714286	3.428571	3.714	5.0	4.154
27	2		Disamatic C3-150, ATC 1230SA	Boy 55 A VV	Visimat billion 90th	Rousseurs FXL21-11	ZHANYING CK7720	Visimat billion 90th	5.0	3.571429	3.0	3.428	4.285	3.877
28	2		Disamatic C3-150, ATC 1230SA	Boy 55 A VV	Visimat billion 90th	Rousseurs FXL21-11	ZHANYING CK7720	Proxima 50th	5.0	3.714286	3.142857	3.714	5.0	4.101
29	2		Disamatic C3-150, ATC 1230SA	Boy 55 A VV	Visimat billion 90th	BZZK VGS112	JUXING CJX0632	Visimat billion 90th	5.0	3.857143	3.714286	3.142	4.285	4.017
30	2		Disamatic C3-150, ATC 1230SA	Boy 55 A VV	Visimat billion 90th	BZZK VGS 112	JUXING CJX0632	Proxima 50th	5.0	4.0	3.857143	3.428	5.0	4.241
31	2		Disamatic C3-150, ATC 1230SA	Boy 55 A VV	Visimat billion 90th	BZZK VGS112	ZHANYING CK7720	Visimat billion 90th	5.0	3.857143	3.428571	3.142	4.285	3.965

Table 13 (continued)

Id	MC	S11	S12	S231	S232	S233	S312	S321	Machine availability	Compatibility	Quality	costs	reuse	PrI
32	2		Disamatic C3-150, ATC 1230SA	Boy 55 A VV	Visimat billion 90th	BZZK VGS112	ZHANYING CK7720	Proxima 50th	5.0	4.0	3.571429	3.428	5.0	4.188
33	2		Hercule Billion H780 200th, ATC 1230SA	HAIJING HJG50	Visimat billion 90th	Rousseurs FXL21-11	JUXING CJX0632	Visimat billion 90th	5.0	3.714286	3.142857	3.142	4.285	3.881
34	2		Hercule Billion H780 200th, ATC 1230SA	HAIJING HJG50	Visimat billion 90th	Rousseurs FXL21-11	JUXING CJX0632	Proxima 50th	5.0	3.857143	3.285714	3.428	5.0	4.103
35	2		Hercule Billion H780 200th, ATC 1230SA	HAIJING HJG50	Visimat billion 90th	Rousseurs FXL21-11	ZHANYING CK7720	Visimat billion 90th	5.0	3.714286	2.857143	3.142	4.285	3.827
36	2		Hercule Billion H780 200th, ATC 1230SA	HAIJING HJG50	Visimat billion 90th	Rousseurs FXL21-11	ZHANYING CK7720	Proxima 50th	5.0	3.857143	3.0	3.428	5.0	4.051
37	2		Hercule Billion H780 200th, ATC 1230SA	HAIJING HJG50	Visimat billion 90th	BZZK VGS112	JUXING CJX0632	Visimat billion 90th	5.0	4.0	3.571429	2.857	4.285	3.967
38	2		Hercule Billion H780 200th, ATC 1230SA	HAIJING HJG50	Visimat billion 90th	BZZK VGS112	JUXING CJX0632	Proxima 50th	5.0	4.142857	3.714286	3.142	5.0	4.191

Table 13 (continued)

Id	MC	S11	S12	S231	S232	S233	S312	S321	Machine availability	Compatibility	Quality	costs	reuse	PrI
39	2		Hercule Billion H780 200th, ATC 1230SA	HAIJING HJG50	Visimat billion 90th	BZZK VGS112	ZHANYING CK7720	Visimat billion 90th	5.0	4.4	3.285714	2.857	4.285	3.914
40	2		Hercule Billion H780 200th, ATC 1230SA	HAIJING HJG50	Visimat billion 90th	BZZK VGS112	ZHANYING CK7720	Proxima 50th	5.0	4.142857	3.428571	3.142	5.0	4.138
41	2		Hercule Billion H780 200th, ATC 1230SA	Boy 55 A VV	Visimat billion 90th	Rousseurs FXL21-11	JUXING CJX0632	Visimat billion 90th	5.0	3.857143	3.714286	3.142	4.285	4.017
42	2		Hercule Billion H780 200th, ATC 1230SA	Boy 55 A VV	Visimat billion 90th	Rousseurs FXL21-11	JUXING CJX0632	Proxima 50th	5.0	4.0	3.857143	3.428	5.0	4.241
43	2		Hercule Billion H780 200th, ATC 1230SA	Boy 55 A VV	Visimat billion 90th	Rousseurs FXL21-11	ZHANYING CK7720	Visimat billion 90th	5.0	3.857143	3.428571	3.142	4.285	3.965
44	2		Hercule Billion H780 200th, ATC 1230SA	Boy 55 A VV	Visimat billion 90th	Rousseurs FXL21-11	ZHANYING CK7720	Proxima 50th	5.0	4.0	3.571429	3.428	5.0	4.188
45	2		Hercule Billion H780 200th, ATC 1230SA	Boy 55 A VV	Visimat billion 90th	BZZK VGS112	JUXING CJX0632	Visimat billion 90th	5.0	4.142857	4.142857	2.857	4.285	4.105

Table 13 (continued)

Id	MC	S11	S12	S231	S232	S233	S312	S321	Machine availability	Compatibility	Quality	costs	reuse	PrI
46	2		Hercule Billion H780 200th, ATC 1230SA	Boy 55 A VV	Visimat billion 90th	BZZK VGS 112	JUXING CJX0632	Proxima 50th	5.0	4.285714	4.285714	3.142	5.0	4.328
47	2		Hercule Billion H780 200th, ATC 1230SA	Boy 55 A VV	Visimat billion 90th	BZZK VGS112	ZHANYING CK7720	Visimat billion 90th	5.0	4.142857	3.857143	2.857	4.285	4.052
48	2		Hercule Billion H780 200th, ATC 1230SA	Boy 55 A VV	Visimat billion 90th	BZZK VGS 112	ZHANYING CK7720	Proxima 50th	5.0	4.285714	4.0	3.142	5.0	4.276

Table 14 Defining the remaining production system possibilities and their characteristics

Id	MC	S11	S12	S231	S232	S233	S312	S321	Machine availability	Compatibility	Quality	costs	reuse	PrI	Pr
10	1	No available machine		Boy 55 A VV	Visimat billion 90th	Rousseurs FXL21-11	JUXING CJX0632	Proxima 50th	4.16667	3.8	4.0	3.6	5.0	4.057	0.812
14	1	No available machine		Boy 55 A VV	Visimat billion 90th	BZZK VGS 112	JUXING CJX0632	Proxima 50th	4.16667	4.2	4.6	3.2	5.0	4.179	0.836
16	1	No available machine		Boy 55 A VV	Visimat billion 90th	BZZK VGS 112	ZHANYING CK7720	Proxima 50th	4.16667	4.2	4.2	3.2	5.0	4.106	0.821
46	2		Hercule Billion H780 200th	Boy 55 A VV	Visimat billion 90th	BZZK VGS 112	JUXING CJX0632	Proxima 50th	5.0	4.285714	4.2857	3.1428	5.0	4.329	0.866
48	2		Hercule Billion H780 200th	Boy 55 A VV	Visimat billion 90th	BZZK VGS 112	ZHANYING CK7720	Proxima 50th	5.0	4.285714	4.0	3.1428	5.0	4.276	0.855

Table 15 A table for defining the production possibilities of the remaining solutions set

Id	MC		S11	S12	S231	S232	S233	S312	S321	Pr	DM	IU	IC	Prd	PrdI	GNW	GNWI
1	1	[‘S11’, ‘S23’, ‘S32’,’ S41’, S51’, ‘S61’, S72’]	No available machine		Boy 55 A VV	Visimat billion 90th	Rousseurs FXL21-11	JUXING CJX0632	Proxima 50th	0.812	1.0	0.833	0.9778	0.899	2	0.999	5
2	1	[‘S11’, ‘S23’, ‘S32’,’ S41’, S51’, ‘S61’, S72’]	No available machine		Boy 55 A VV	Visimat billion 90th	BZZK VGS 112	JUXING CJX0632	Proxima 50th	0.836	1.0	0.833	0.9778	0.908	5	0.999	5
3	1	[‘S11’, ‘S23’, ‘S32’,’ S41’, S51’, ‘S61’, S72’]	No available machine		Boy 55 A VV	Visimat billion 90th	BZZK VGS 112	ZHANYING CK7720	Proxima 50th	0.821	1.0	0.833	0.9778	0.903	3	0.999	5
4	2	[‘S11’, ‘S23’, ‘S32’,’ S41’, S51’, ‘S62’, S72’]	No available machine		Boy 55 A VV	Visimat billion 90th	Rousseurs FXL21-11	JUXING CJX0632	Proxima 50th	0.812	1.0	0.833	0.9778	0.899	2	0.974	3
5	2	[‘S11’, ‘S23’, ‘S32’,’ S41’, S51’, ‘S62’, S72’]	No available machine		Boy 55 A VV	Visimat billion 90th	BZZK VGS 112	JUXING CJX0632	Proxima 50th	0.836	1.0	0.833	0.9778	0.908	5	0.974	3

Table 15 (continued)

Id	MC		S11	S12	S231	S232	S233	S312	S321	Pr	DM	IU	IC	Prd	PrdI	GNW	GNWI
6	2	[‘S11’, ‘S23’, ‘S32’,’ S41’, S51’, ‘S62’, S72’]	No available machine		Boy 55 A VV	Visimat billion 90th	BZZK VGS 112	ZHANYING CK7720	Proxima 50th	0.821	1.0	0.833	0.9778	0.904	3	0.974	3
7	3	[‘S11’, ‘S23’, ‘S32’,’ S42’, S51’, ‘S61’, S72’]	No available machine		Boy 55 A VV	Visimat billion 90th	Rousseurs FXL21-11	JUXING CJX0632	Proxima 50th	0.812	1.0	0.833	0.9556	0.896	1	0.944	1
8	3	[‘S11’, ‘S23’, ‘S32’,’ S42’, S51’, ‘S61’, S72’]	No available machine		Boy 55 A VV	Visimat billion 90th	BZZK VGS 112	JUXING CJX0632	Proxima 50th	0.836	1.0	0.833	0.9556	0.904	4	0.944	1
9	3	[‘S11’, ‘S23’, ‘S32’,’ S42’, S51’, ‘S61’, S72’]	No available machine		Boy 55 A VV	Visimat billion 90th	BZZK VGS 112	ZHANYING CK7720	Proxima 50th	0.821	1.0	0.833	0.9556	0.899	2	0.944	1
10	4	[‘S12’, ‘S23’, ‘S32’,’ S41’, S51’, ‘S61’, S72’]		Hercule Billion H780 200th	Boy 55 A VV	Visimat billion 90th	BZZK VGS 112	JUXING CJX0632	Proxima 50th	0.866	1.0	0.765	0.9556	0.900	2	0.996	5

Table 15 (continued)

Id	MC	S11	S12	S231	S232	S233	S312	S321	Pr	DM	IU	IC	Prd	PrdI	GNW	GNWI
11	4	[‘S12’, ‘S23’, ‘S32’,’ S41’, S51’, ‘S61’, S72’]	Hercule Billion H780 200th	Boy 55 A VV	Visimat billion 90th	BZZK VGS 112	ZHANYING CK7720	Proxima 50th	0.855	1.0	0.765	0.9556	0.896	1	0.996	5
12	5	[‘S12’, ‘S23’, ‘S32’,’ S41’, S51’, ‘S62’, S72’]	Hercule Billion H780 200th	Boy 55 A VV	Visimat billion 90th	BZZK VGS 112	JUXING CJX0632	Proxima 50th	0.866	1.0	0.765	0.9556	0.900	2	0.971	3
13	5	[‘S12’, ‘S23’, ‘S32’,’ S41’, S51’, ‘S62’, S72’]	Hercule Billion H780 200th	Boy 55 A VV	Visimat billion 90th	BZZK VGS 112	ZHANYING CK7720	Proxima 50th	0.855	1.0	0.765	0.9556	0.896	1	0.971	3
14	6	[‘S12’, ‘S23’, ‘S32’,’ S42’, S51’, ‘S61’, S72’]	Hercule Billion H780 200th	Boy 55 A VV	Visimat billion 90th	BZZK VGS 112	JUXING CJX0632	Proxima 50th	0.866	1.0	0.765	0.9778	0.904	4	0.941	1
15	6	[‘S12’, ‘S23’, ‘S32’,’ S42’, S51’, ‘S61’, S72’]	Hercule Billion H780 200th	Boy 55 A VV	Visimat billion 90th	BZZK VGS 112	ZHANYING CK7720	Proxima 50th	0.855	1.0	0.765	0.9778	0.900	2	0.941	1

Table 16 A table for defining the importance percentages of the producibility influence factors using AHP

Alternatives	Results	
Manufacturing Process selection	32.5%	🟩
Material Availability	29.2%	🟩
Machinability	20.3%	🟩
Part Family Compatibility	17.9%	🟩

eliminated by our algorithm. This is because system engineers are the only ones responsible for eliminating these solutions, purchasing the missing machines or find a supplier for the manufacturing of the parts which cannot be processed in the factory.

4.2.3 Step10: Verification

This step widely depends on the results obtained in earlier phases. The system engineer is meant to choose the best solution that better meets the needs developed in the SysML requirements diagram and its most convenient production system.

In our case study, there exists, as we can notice from the Table 15, two producibility indices solutions equal to 5 which are highlighted by the blue lines. The GNWI performance index is equal to 5 in the first solution (solution number 2 in the Table 15) while it's equal to 3 in the second one (solution number 5 in the Table 15). For this reason, solution 2, which corresponds to the first solution displayed in the Table 18, was chosen as the best solution. It is composed of several sub-systems. A co-molded plastic bloc used as a solution for the housing of the Electronic Throttle body. Over molded plastic gears are included to adapt mechanical energy. A metal plate shaft and a plastic throttle plate are employed as solutions for the opening and the closing of the airflow passage. A direct current (DC) motor is utilized to convert energy. To Measure the throttle plate angle, the double-track potentiometer is put to work. The two last components are connected to a PI calculator which receives information about the throttle plate position and compares it to pedal position measured through a second potentiometer which translates the driver's need for controlling the throttle body motor. Furthermore, two security springs are used for the purpose of insuring the opening and the closing security of the throttle plate. This model (solution 2) is chosen though the co-molded machine needed for the machining of the electronic throttle body housing is missing in the factory. It can also be noted that the raw materials cost of the solutions comprising the co-molded housing is less expensive than the other solutions composed of molded plastic housing. Moreover, the chosen solution is the only one characterized by a performance global weight and a producibility indices equal to 5 (maximum value).

As for the production system, the chosen solution, identified by the number 14 in the Table 14, is the one in which the Proxima 50th, JUXING cjx0632, BZZK VGS 112, Visimat Billion 90th and Boy 55 AVV machines are used in order to manufacture the components of the chosen solution.

As to the electronic throttle body housing, it will be outsourced with a suitable cost less expensive than that of the global solution S12.

Finally, the SysML activity diagram is used to determine functional structure of the ETB production process as shown in Fig. 19 which demonstrates how the flows of both materials and parts can lead to final products.

5 Conclusion

Today, the worldwide competitiveness between modern technical-product industries is centered around the improvement of the quality and the speed of Today, the worldwide competitiveness between modern technical-product industries is centered around the improvement of the quality and the speed of innovation of these new products with a decrease in their development time and cost. This has ended up being more and more complicated due to the increase in the complexity of modern products.

The complexity of the development of new products has therefore increased iterative loops between designers, manufacturing engineers and other specialists. These iterative loops are responsible for boosting the development time and cost. This paper aims at developing a new methodology approach which brings concurrent engineering and system engineering together in order to reduce iterative exchange loops.

Our methodology is mainly based on the SBCE principles adopted to simplify collaboration between the participants and the MBSE model in order to cope with the developed models and ease their convention into data matrices. This model helps simplify the application of the SBCE approach principles through preliminary identify clients' needs, then developing a set of solutions and finally converging towards an optimal system solution and the most convenient production system. Added to that, it helps progressively eliminate the system solutions which are impossible to achieve based on filters throughout the different design stages. The first filter rests upon the system performance using clients' needs and their importance percentage to compute, for each solution sub-system/system, a performance index through applying the developed equations and matrices in order to converge towards a limited number of system solutions.

Table 17 A table for defining the remaining subsystems solutions characteristics

Id	Label	Label2	Components	Materials type	Materials	Machining	Machinability	Material availability	Length	Width	Weight	Height	Volume	Number
1	S11	S11	One bloc, co-molded, bi-plastic body	Plastic	0.5 glass-filled nylon, 0.5 PPS	Co-molding	5.0	5.0	120.0	75.0	490.0	110.0	350.0	1000.0
2	S12	S12	One bloc, molded, plastic	Plastic	PPS	[molding machines][4axix machining center]	5.0	3.0	120.0	75.0	490.0	110.0	350.0	1000.0
3	S23	S231	Plastic gearwell over molded	Plastic	PPS	Over molding machines	5.0	3.0	42.5	42.5	22.0	11.0	15.59	1000.0
4	S23	S232	Plastic gearwell molded	Plastic	PPS	Molding machines	5.0	5.0	62.5	62.5	128.0	30.0	92	1000.0
5	S23	S233	Metal pinion	Metal	raw steel	Sintering machines	5.0	4.0	20.0	20.0	35.0	14.0	4.396	1000.0
6	S32	S312	Metal plate shaft	Metal	raw aluminum	CNC turning machine	5.0	5.0	100.0	15.0	46.0	15.0	17.662	1000.0
7	S32	S321	Plastic throttle plate	Plastic	PEI	[Stamping press machine, molding machines	5.0	3.0	50.0	50.0	22.0	8.0	15.7	1000.0
8	S41	S41	Dc motor	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
9	S42	S42	Stepper motor	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
10	S51	S51	Double track potentiometer	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
11	S61	S61	PI controller	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
12	S62	S62	PID controller	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
13	S72	S72	Two springs	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	

Id	Purchasing	Manufacturing	Ability	RMPFTNP	Machines1	Machines2
1	0	1	No	1764.0	No available machine	
2	0	1	Yes	2793.0	Disamatic C3-150, Hercule Billion	ATC 1230SA
3	0	1	Yes	125.4	HAIJING HJG50, Boy 55 A VV	
4	0	1	Yes	729.6	Visimat billion 90th	
5	0	1	Yes	23.59	Rousseurs FXL21-11, BZZK VGS112	
6	0	1	Yes	82.8	JUXING CJX0632, ZHANYING CK7720	
7	0	1	Yes	396.0	Visimat billion 90th, Proxima 50th	
8	1	0				
9	1	0				
10	1	0				
11	1	0				
12	1	0				
13	1	0				

Table 18 Chart of missing machines definition

Id	Set	Label	Manufacturing	RMP	GNW	GDW
1	1	[‘S11’, ‘S23’, ‘S32’,’ S41’, S51’, ‘S61’, S72’]	Lack 1 machines to make S11	3121.39	0.999331	0.977778
2	1	[‘S11’, ‘S23’, ‘S32’,’ S41’, S51’, ‘S62’, S72’]	Lack 1 machines to make S11	3121.39	0.973934	0.977778
3	1	[‘S11’, ‘S23’, ‘S32’,’ S42’, S51’, ‘S61’, S72’]	Lack 1 machines to make S11	3121.39	0.944595	0.955556
4	2	[‘S12’, ‘S23’, ‘S32’,’ S41’, S51’, ‘S61’, S72’]	PIOC	4150.39	0.996616	0.955556
5	2	[‘S12’, ‘S23’, ‘S32’,’ S41’, S51’, ‘S62’, S72’]	PIOC	4150.39	0.971219	0.955556
6	2	[‘S12’, ‘S23’, ‘S32’,’ S42’, S51’, ‘S61’, S72’]	PIOC	4150.39	0.941881	0.977778

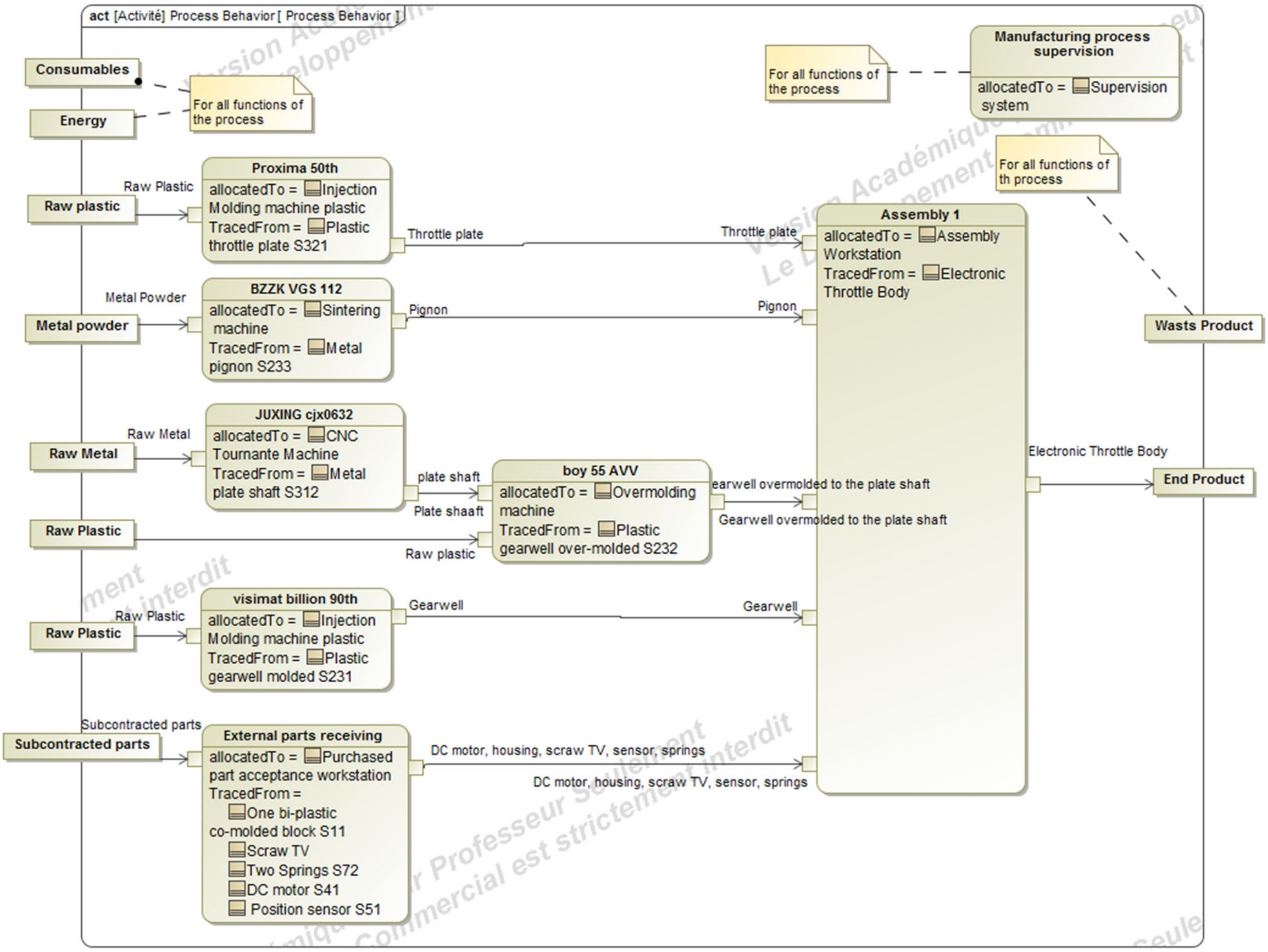


Fig. 19 The functional structure of the ETB production process

Afterwards, this approach suggest the system development production process during the preliminary design phases proposing the set of machines available in the industry and that can be used for the production of the remaining system solutions. In this phase, another filter related to the introduction of new constraints linked to the system production interferes aiming at reducing, more and more, the number of the remaining system solutions. Therefore, the AAM and ARPU algorithms application helps find the set of possibilities for production lines in order to better converge towards the optimal system solution on the one hand and find the most suitable production system by decreasing the number of choices for machines at the beginning of this phase on the other hand. This helps indicate whether the production of such possible system solution is possible and define the riming necessary machines for the production of such system.

Briefly, the major aim of this developed new approach is reducing the time and the development cost through restricting feedback and minimizing its default risk at advanced stages. The clarification of the detailed stages facilitates the implementation of the SBCE approach and, thus helps factories apply it in order to improve the development process of new complex products.

6 Future works

As a future research, we will consider ameliorating our algorithms through a direct reading of the design data from the SysML model using python in order to automate the treatment process and introduce the detailed design phase in this current approach.

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