Preprints of the
16th IFAC Symposium on Information Control Problems in Manufacturing
Bergamo, Italy. June 11-13, 2018

Modular design of production systems tailored to regional market requirements: A Frugal Innovation perspective

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Abstract: Tailoring products for emerging regional markets under a frugal innovation perspective is a strategic opportunity for companies' competitiveness. However, this entails managing the co-evolution of adapted products and production systems for affordable manufacturing costs. In this paper, a modular design process is proposed to support the configuration of production systems adapted to regional market needs. It includes the matching of product and equipment modules, the line balancing, and the system design into an integrated problem. This modular approach supports the propagation of requirements in the product and system co-design process. The results are demonstrated in an automotive real case study.

Keywords: Modular approach, Assembly system, co-evolution, frugal innovation, system configuration

1. INTRODUCTION

Producing innovative products for new regional markets with optimal cost and time requires well understanding of customers' needs and a co-evolution of the production strategy taking in consideration the capabilities, constraints and resources available in the targeted market. Frugal innovation theory provides interesting directions to support such problems (Tiwari et al., 2012). "Frugal" concept is an aggregation of six attributes: Functional; Robust; User-friendly; Growing; Affordable; and Local (Berger 2013).

In the case of enterprises specialized on the development and installation of machineries and production systems (PS), when the client requests design and installation of a whole manufacturing plant in a specific market, the company needs to deal simultaneously with various requirements coming from the target market of the end products (to be produced by the target PS) and those related to the plant implementation constraints. Indeed, due to specific cultural, social and legal policies, usage conditions and quality standards change from one region to another. Requirements will vary as well.

Thus, the company needs flexible mechanisms to easily adapt its current solutions for every use context, through smart management of requirements and constraints propagation along the stakeholders' chain involved in the PS project. In this paper, modularity for design is proposed to support the configuration of frugal production systems (PS) tailored to new regional markets. This approach is based on the concept of module and exploits knowledge management facilities, integrated in a new method of production lines configuration. Knowledge based systems are often used as potential solution to manage large variety of knowledge in the shop floor within the factory of the future perspective (Laroche et al., 2016). Section 2 introduces the modularity-based conceptual solution for requirements propagation management in case of PS design. Sections 3 and 4 describe the knowledge-based configuration framework implementing the modular solution. Section 5 illustrates the application in industrial use case.

2. MODULARITY FOR REQUIREMENTS PROPAGATION MANAGEMENT IN DESIGN PROJECT FOR REGIONAL MARKET

2.1 Requirement propagation along the development process

Designing new PS for the production of frugal products tailored to a regional market is a complex process (Ballard et al., 2001). Depending on the type of the target end-product (produced by the PS), the target market and the location of the future production line, two options are possible when addressing frugal PS for new regional markets. The first one is the realisation of a manufacturing plant in different location from the target end-product. The second is to install the plant in the same market, exploiting maximum of local production capabilities.

In both cases, several stakeholders are involved to provide variety of requirements, which can be distinguished as main frugality criteria to be considered in the design process of the target PS: (1) Market requirements describing the consumption habits in the target end-product market; (2) Local production sites requirements focus on the future usage conditions of the PS. It concerns the plant map, security rules, energy standards, Workers' morphologies and traits, etc. and (3) Production requirements give the detailed needs in terms of manufacturing functions, to provide the desired products.

Regarding the variety of requirements described above, a critical stage concerns their classification regarding the final objectives of the development process (Jiao et al., 2006).

2.2 Modular-approach for production system design

To guarantee the consistency of the final solution, co-evolution strategy is needed to manage the propagation of engineering changes at different levels (Tolio et al., 2010). The power of modularity to support co-evolution is often discussed in the literature since it consists of decomposing complex systems into independent but interconnected parts that can be treated as conceptual, logical, physical or organizational units (Sako et al., 2005). The modular design process aims at connecting various modules into a suitable and consistent architecture. It allows multiple product variants' definition, using product family concept and configuration management rules (ElMaraghy et al., 2013). The system architecture describes the way by which the functions are arranged into physical units and how these units interact through their interfaces to implement the functions (Ulrish et al., 2006).

The proposed modularity-based approach suggests organizing the PS design process around two pillars, namely process definition in terms of processing modules and PS architecture configuration as a consistent combination of workstations. A workstation is itself composed by a set of modules. Figure 1 synthetizes the elements of the modular approach. The PS design process starts from the process definition pillar while the requirements propagation concerns three dimensions. The third additional dimension named "end-product structures" is considered in this work as the only input for the PS design process. Since the end-product is developed by other companies, this dimension is out of the scope of the proposed design approach.

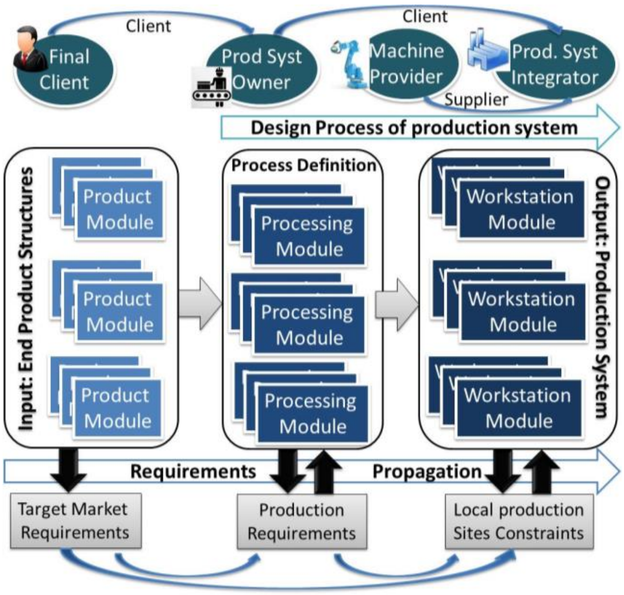

Fig. 1. Global overview of the modular approach.

In this approach, a processing module is defined as a set of processes and/or equipment to achieve some manufacturing objectives. It is described by a set of characteristics: (i) objectives of the related operation (ii) some features of the concerned product module(s), (iii) transformation/assembly constraints, and (iv) region dependent features.

A workstation module is defined as a cluster of processing modules arranged in a specific way to perform some manufacturing operations on some product module(s). It can be configured dynamically based on interface connectivity, flow of information, flow of material or processing steps, etc.

Several alternatives of processing module can be identified to perform the same manufacturing operation, and then several workstation module alternatives are possible. As well, several PS structures alternatives can be built from various workstations combinations and are differentiated by a set of key performance indicators (Amrina et al., 2011). By using modularity to connect various requirements to a set of predefined and customizable solutions, the PS design process will be conducted as a knowledge-based configuration of predefined modules representing both processes and physical items. However, customization of some parameters could be realized by adding new modules.

Fig. 2. Global method of modular PS design process.

The navigation between the above design pillars is achieved through a set of transformation rules, to be considered as a kind of PS design rules (Black 2007). Accordingly, the PS design process is conducted within four steps (Figure 2). After collection, classification and analysis of the requirements, the step of modules constitution supports the definition and classification of potential solutions' alternatives to be used in the next step. Knowledge-based mapping consists on the application of transformation rules to connect modules alternatives from various pillars. The last step is the production line configuration for selecting optimal PS solution. These steps are detailed respectively in sections 3, 4 and 5.

2.3 Problem statement

An industrial use case is conducted as a context of the proposed research. Comau is a global supplier of industrial automation systems and services. Comau offers its proficiency as System Integrator and its complete engineering solutions to resolve all manufacturing process issues.

The use case analysed in this research regards the powertrain assembly line as a serial process to assemble supplied modules (engines block, cylinder head, transmissions, etc.). The shape of an assembly line can vary from a simplest shape (straight line) to a complex layout with loops and turns to develop the line in a constrained existing plant.

During the preliminary design phase, customer requirements are transformed into an initial physical design solution, represented by a graphical arrangement (Mountney et al., 2007), analysis and cost estimation. Based on these requirements, engineers use their own knowledge and try to recall past layout ideas for the design of the new production line. According to Efthymiou et al. (2013), about 20% of the designer's time is dedicated to searching and analysing past available knowledge. At the same time there is a need of considering at an industrial level different regional requirements related to the destination plant of the manufacturing equipment. Then, the aim of the Standard and R&D department is to find efficient technical solutions that can be built and customized to satisfy the widest possible range of requirements. These technical solutions are based on a modular approach to facilitate flexibility and scalability of machines and systems.

3. KNOWLEDGE BASE FRAMEWORK TO SUPPORT REQUIREMENT PROPAGATION MANAGEMENT WITH MODULAR APPROACH

3.1 Modules Constitution of a production system

Respecting the above definitions, an example of processing module is given in Figure 3 as a cluster of assembly / transformation processes applied on the studied use case. The performance indicators distinguishing processing modules in this use case are: automation levels, costs, level of material used and processed, and energy consumption among others.

Regarding the use case of interest from a physical point of view, an assembly line is composed by a series of workstations which perform serial operations connected by a conveyor system. The product which is being assembled goes from one workstation to another on a pallet carried by the conveyor system. Inside the workstation, the assembly process takes place. Once the assembly process is finished, the pallet is released and is conveyed to the next workstation.

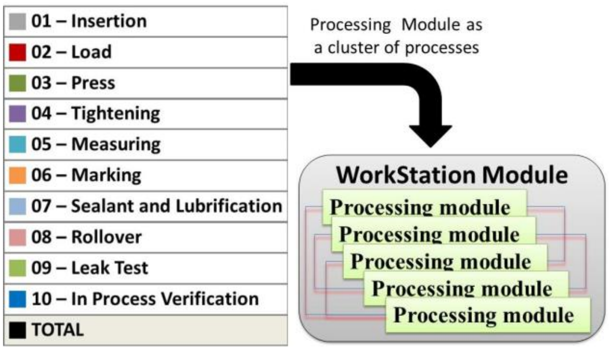

Fig. 3. Example of processing module in a workstation.

Following the modular approach, the same standardization concept is applied both at equipment (i.e. machines, pallet and conveyors) and processes levels. Process Modularity is done by analysing all the recurring assembly processes and grouping together the processes that involve similar technical features. At a high level, the modularity of an entire assembly line can be divided into three macro categories: workstation, conveyor system and pallet. The workstations modularity covers the range of typical assembly stations.

There are three basic assembly systems' types to be considered in the workstation modularity: manual assembly (carried out by human assemblers, usually with the aid of simple power tools); fully automated assembly systems; and hybrid assembly systems that combine human assemblers and automated mechanisms and robots. Independently from the internal process and the type of machine, the "sub-sections" defining the modules in a workstation are the following: Structure; Motion Equipment; Process Equipment; and Controls Equipment.

The "Structure" identifies the mechanical structure of the assembly station. Parts of the "motion equipment" are the objects that are placed on top of the standard structures to hold or move the equipment needed to perform the specific processes. The main peculiar feature of the motion equipment is that they are transversal to the defined process clusters. This means that the same motion equipment can be applied to different processes. For instance, the Comau robots can be considered as motion equipment as they can move a generic end-effector that has to perform a specific process.

The "process equipment" module is strictly connected to the operation which has to perform the related cluster too. An example of process equipment could be a gripper used to take and move the crankshaft from the feeder to its position on the cylinder block, it is designed for the specific task and it could not be applied, to tighten bolts or to apply the sealant. All the electric, pneumatic and fluidic connection is part of the "control equipment" together with the software of the workstation, if applicable. Figure 4 explains the concept of equipment standardization applied to a SmartRob automatic workstation. The workstation structure is highlighted in orange (one module). The motion equipment are highlighted in green (three modules) while the process specific equipment is highlighted in blue (one module).

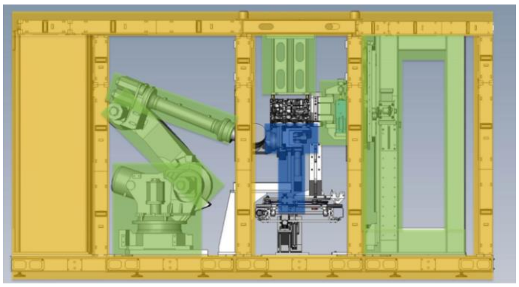

Fig. 4. Equipment modularity applied to SmartRob structure

3.2 Implementation of the modular model in KB framework

A knowledge-based (KB) framework has been developed to support the design of a new PS with regional and frugal features. The KB is able to support and/or automate activities in the preliminary configuration of a new PS at a parametric design level, satisfying all the requirements. All the data are in digital format and all activities are virtualized; moreover, the KB tool manages the domain knowledge and the company's know-how. It supports the experts to produce and evaluate in a short time different solutions of a PS, respecting the same set of requirements and with different costs. The output is a high level configuration of PS, without details that are not required in the preliminary quotation. Moreover, the model of the plant configured can be the input for the following design steps (i.e. embodiment and detailed design).

The configuration process of a new PS starts with the acquisition of the requirements (production levels, target market and local production site) and the translation of them into design specifications. Then, all the activities necessary to assembly an engine head have been defined; they depend on the type and characteristics of the end-product. Identified activities have to be arranged in a logical sequence that respects technological priority. The next task concerns the allocation of the defined process activities to a set of workstations. The KB system selects the suitable workstations to perform the assembly sequence with respect to the required level of automation, which can depend on frugal requirements.

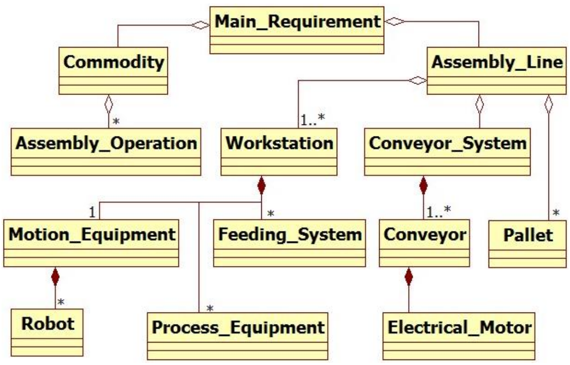

Fig. 5. Simplified UML Class Diagram of the PS.

Fig. 5 shows a simplified UML Class Diagram of the logic architecture of a PS. The workstations characteristics and equipment, the buffers and conveyors are described into the variable of the corresponding object as well as the methods representing the configuration rules. The modular approach has been translated in a consistent way in the O-O architecture. The requirements propagation (i.e. inheritance) occurs automatically according to O-O main features. The next step is the assembly line balancing and a multivariable optimization, useful, to determine how to perform the clustering of assembly tasks, dimension the workstation, size buffers and optimize the line. This will be discussed in detail in the next section.

4. PRODUCTION SYSTEM CONFIGURATION USING MODULAR APPROACH

4.1 Problem definition and outline of the approach

The objective of this phase is to design the assembly system able to produce the product required by the customer, under region-dependent specifications, at a given desired throughput. The product structure is provides input in terms of subcomponents and assembly precedence graph. This describes the set of assembly tasks (or operations) that should be performed to obtain the product, together with specific precedence constraints. To execute the operations, different types of workstation architectures can be selected, which vary with respect to technological content, the set of modules, degree of automation, investment and lifecycle costs. The lifecycle cost is the cumulative operational costs of the system over the entire predicted useful life, including energy, personnel, inventory, and maintenance. These costs depend on the local production site requirements and are retrieved by the requirement propagation analysis. The production modules composing the workstations are assumed to be prone to failures, whose Mean Time To Failure (MTTF) and Mean Time To Repair (MTTR) are stored in the company database and are considered as the problem input data. The associability of tasks to workstation types is obtained in input from the KB Engineering tool, described above.

The assembly system design problem consists of: sequencing and assigning the tasks to workstations under precedence constraints, selecting the type of workstations, defining the capacity of each buffer between workstations in order to respect the target throughput and factory floor space limitations, considering the investment cost and the lifecycle cost of the system as objectives in a multi-objective decision making environment. The consideration of multiple objectives is a strategic requirement from Comau. Indeed, in the early stage system design, customers usually prefer to be provided with multiple design options, differing in investment and lifecycle costs, in order to take decisions on the basis of a wider set of considerations other than the minimum investment cost. The system configuration problem described above entails the solution of a non-linear optimization problem. Indeed, from the system engineering theory, it is known that the system throughput is a non-linear function of the buffer sizes. For this reason, running an exact approach to explore the solution space may easily become computationally impracticable. In the literature, the task assignment problem and the buffer allocation problem are treated sequentially and in isolation (Hu et al., 2011). This leads to sub-optimal configurations.

To overcome this problem, in this paper a recursive approach is proposed. It is composed of three major steps, namely (i) line balancing, (ii) buffer allocation, and (iii) physical layout refining. Given the multi-objective nature of the problem, the first two steps are iteratively applied and orchestrated through modeFRONTIER, a multi-objective optimization environment allowing the user to define a workflow and the capability of coupled execution with external tools. The workflow architecture in mode FRONTIER and the data flow among the two modules is represented in Figure 6.

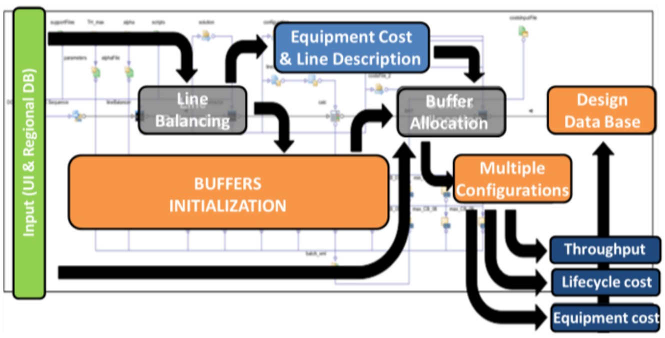

Fig. 6. modeFRONTIER multi-objective optimization workflow.

4.2 Line-balancing

The line-balancing problem sequences and allocates assembly tasks to the workstation in the line. It has been extensively studied in the literature (Sivasankaran et al., 2014). This problem should consider the specifications of the assembling process (alternative operations sequences, additional constraints among the operations), the characteristics of the workstations (process capability, operation times, reliability parameters, cost) but also a wide set of constraints deriving from the propagation of regional requirements. These requirements could constrain the sequence of operations to be implemented, the selection of specific equipment modules, as well as the execution of some operations. For example, aiming at frugal innovation, the regional characteristics could push towards a higher or lower degree of automation to manage the impact of different wage or skill levels. Moreover, different materials in the product may be used, calling for different assembly processes. The aim of the formulated line-balancing problem is to minimize the deviation of the workload among the workstations:

$$\min \max_{u,v\in S,u<v} \left| \sum_{i\in I,m\in M} \mu_{i,m}\, x_{i,m,u} - \sum_{i\in I,m\in M} \mu_{i,m}\, x_{i,m,v} \right|$$

Where S is the set of stations, I is the set of tasks, M is the set of modular equipment types that can be installed into the stations, $\mu_{(i,m)}$ is a the processing time of operation i when executed on module type m, $x_{(i,m,u)}$ is a Boolean assignment variable assuming value 1 if operation i is assigned to equipment type m in station u, 0 otherwise. This linear optimization problem considers constraints related to the minimum throughput, the available physical floor space defined with simple geometries, and a maximum investment budget. By iteratively varying this last parameter, more automated workstation types are favoured, thus supporting a wider exploration of the solution space.

4.3 Buffer allocation

The output of the line-balancing problem is the selection of a set of workstations with the associated processing time, given by the sum of the assigned task times. However, due to the random failures of each module composing a workstation, the size of the buffers among workstations has a significant impact on the system throughput. To address this problem, an additional multi-objective buffer allocation phase is operated through modeFRONTIER, under a given minimal throughput constraint. A performance evaluation kernel, based on approximate analytical methods (Colledani et al., 2005) is integrated in modeFRONTIER. This tool predicts the throughput of the system as a function of reliability parameters, workstations processing times and given buffer size distributions. The modeFRONTIER optimization engine explores the feasible set of buffer sizes and reports the solutions as points in the Pareto analysis. Then, a new value of the minimal budget is generated and provided to the Line Balancing step for exploring a different workstation selection solution.

4.4 Physical-layout refining

Once the Pareto front is generated for specific regional design requirements, the Pareto optimal solutions can be selected. With the objective to provide to the customer by a realistic view of the designed system, its workstations, and its layout, a physical-layout refining stage is proposed. In this stage, the positions and the types of the selected workstations as well as the buffer sizes corresponding to the Pareto optimal solution are retrieved from the solution database. Moreover, the 3D CAD files of the workstation archetypes are downloaded from the company Product Lifecycle Management (PLM) system. As a consequence, realistic 3D views of the designed layouts can be produced that can be shown to the customer for selection and improvement. In the next section, the main outcomes from the application of the approach to the Comau industrial case are discussed.

5. INDUSTRIAL USE CASE APPLICATION OUTCOMES

This section reports the main outcomes from the application of the proposed approach to the Comau industrial case. The chart provided in output by the production system configuration approach for the Comau powertrain case are reported in Fig. 7, considering requirements from the EMEA Region, characterized by high labour and supply costs.

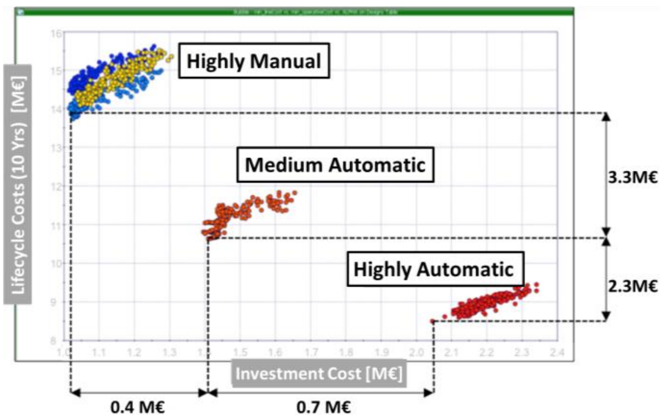

Fig. 7. Pareto Front for multi-objective optimization in EMEA Region.

The following considerations hold:

- In the EMEA region, highly manual solutions entail a lower investment cost than highly automated solutions. However, highly automated solutions are beneficial in terms of lifecycle costs. Indeed, the cost of the manual workforce is more prominent than the other operational costs that are higher for more automated solutions (i.e. energy costs).
- The difference in lifecycle costs between the Pareto-optimal highly automated and highly manual solutions is significant over a ten-year horizon. This means that the higher investment cost of the automated solution, with respect to the manual solution, is easily paid back by savings in lifecycle costs.

As a conclusion, the best possible system design solution for the EMEA Region would be the high automated system. The 3D layout of the most attractive solution is reported in Figure 8. As it can be noticed, the optimal system configuration is strongly affected by the regional requirements. Neglecting the regionalization aspects in the design process can easily lead to sub-performing and sub-optimal configurations.

The developed modular production system design approach and the related tools are able to quantify in economic terms and visualize in technical terms the effect of this market regionalization on design decisions, thus representing a powerful strategic decision support tool to be used by system integrators during the interaction with the customer.

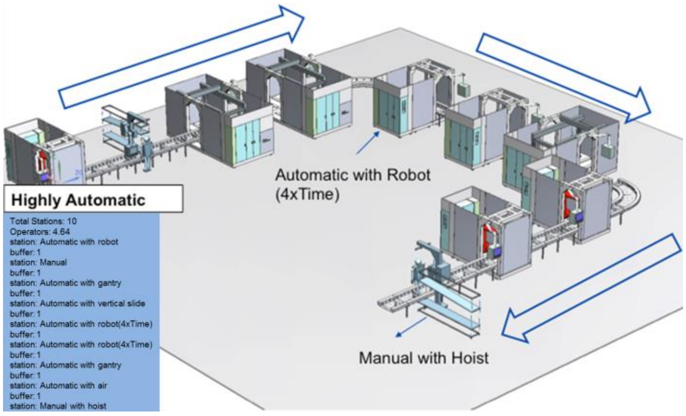

Fig. 8. Pareto-optimal highly automated solution for EMEA Region.

6. CONCLUSION

Considering customer requirements in the design process of a manufacturing system is already a complex task and is has a great impact on the final configuration. This is more challenging when there is a need to consider additional regional requirements related to the manufacturing site and the final product user location. In this paper, the use of modularity as potential enabler to support knowledge representation and reuse in the design process of production systems is discussed. The presented methodology provides an integrated decision support tool able to combine a set of inputs, including product and regional features, and provides a consistent and optimized first-time-right design of the manufacturing system, including 3D visualization.

The application of the proposed approach to a complex real industrial case shows that the regional requirements strongly affect the optimal system solution. Moreover, the method tested in a real industrial environment, shows a great potential of the adopted solution to reduce time and cost of the early-stage system design. By adopting the proposed approach and the related tools, the system integrator is provided with the possibility to digitally test several system configurations, and present to the customers multiple solutions under a multi-objective environment. Future results will concern the application of the approach to different manufacturing contexts, including flexible robotic assembly lines, closed-loop lines and lines with parallel stations.

AKNOWLEDGEMENT

These results were conducted within the project "ProRegio" (customer-driven design of product-services and production networks to adapt to regional market requirements). This project has received funding from the European Union's Horizon 2020 research and innovation program under Grant Agreement N° 636966. The authors would like thank the industrial partners involved in this research.

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