Improving Manufacturing System Design by Instantiation of the Integrated Product, Process and Manufacturing System Development Reference Framework

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Abstract. With Industry 4.0 and the changing dynamics of markets, assisting in designing, modifying, or improving manufacturing systems at different scales becomes necessary, both in large manufacturers and SMEs. Enterprise modelling architectures support the specific description of various layers to assist in the product lifecycle development by reusing general models that can be tailored to particular scenarios through instantiation processes. This work improves the development of manufacturing systems through partial and particular instantiated models based on the Integrated Product, Process and Manufacturing System Development reference framework. Furthermore, this model benefits from the characterization of different industrial sectors to collect tools and activities to avoid developing manufacturing systems anew. In this way, the proposed solution is to create partial models to assist in the design of different manufacturing scenarios: (i) product transfer, (ii) technology transfer and (ii) manufacturing system design. Case studies are instantiated to prove the effectiveness of this framework, in which the particular project activities are developed, and finally, the results assessed by qualitative and quantitative parameters to allow performance measurement.

Keywords: Industry 4.0, Enterprise Engineering, Manufacturing system modelling, Reference Model, Instantiation.

1 Introduction

Manufacturing capabilities have always depended on available technology [1]. The evolution of electronics and computational systems allowed greater control and precision in transformation processes, as well as faster and more continuous production of products demanded by society [2]. Specific and coordinated activities are required to optimise resources as market behaviour pushes preferences towards differentiated and personalised products to meet particular consumer needs [3]. Industry must be able to react to changes quickly and cost-effectively to survive in this new manufacturing environment, thus, creating new challenges for the construction and management of manufacturing systems (MS) [4]. MS require strategic and multidisciplinary planning that design methodologies must assist. It is essential to emphasise the structured creation of these systems as that is where most companies fail in a given time, either due to poor planning or incorrect management of available resources, as considerable investments are required for the creation of a manufacturing plant. It becomes imperative to improve MS development by gathering tools and structuring design activities to be used across different industrial sectors to streamline the processes of creation, construction and evaluation of these complex organisations. Acquiring the necessary strategic skills represent a challenge that many manufacturing companies are facing for speeding up the production system design and optimisation and some appropriate tools and models must be provided that are easily adapted to the needs and unique characteristics of some enterprises. Section 2 is a brief summary of the IPPMD, its roots on enterprise engineering and how it is used to develop the product lifecycle. Section 3 centres on the instantiation for different manufacturing system designs, the workflow of the methodology from decision diagrams to instantiation mappings. Furthermore, Section 4 synthesizes three case studies that elaborate on the development of the proposal to three different design scenarios. Lastly, in Section 5, the conclusions and future work of this article are reported.

2 IPPMD To Design Integrated Manufacturing Systems

Enterprise Architecture frameworks have been created to allow the structured creation of enterprises to deploy systematic engineering practices. The ISO-19439 standard provides a unified concept for enterprise engineering activities that enable the interoperability of various modelling architectures [5]. However, these heavyweight frameworks create a problem increasing the complexity of its adoption among diverse industry sectors. Then, fully customization for a given scenario, utilizing instantiation, allows to inherit the main characteristics and structures of a core model to be adapted to specific characteristics in different levels: (i) general, (ii) partial and (iii) particular. General models gather an extensive set of knowledge that is useful to design any enterprise from different viewpoints. Then, partial models gather common characteristics for a given context with a reusable set of characteristics to develop solutions in certain engineering activities. The Integrated Product, Process and Manufacturing System Development (IPPMD), is a lightweight framework that arises from Enterprise Engineering standards and allows straightforward creation of particular instances to assist in the development of the product lifecycle in different sized enterprises operating in a diversity of productive sectors [6][7][8]. IPPMD has been successfully implemented in several environments, and there is extensive literature that delves into the use of the methodology [9][10][11][12]. The IPPMD consists of three entities that constitute the product lifecycle: (i) product design, (ii) process selection and (iii) manufacturing system development [13]. The third entity supports the design and development of MS with different characteristics, diverse progress stages and operating under specific business scopes to optimise resources, detect opportunity areas and gain competitive advantage. To this extent, instantiation advantage is gained by the integration of different tools guided by decision workflows to include a specific set of engineering activities focused on improving: (i) strategic planning, (ii) resource management, and (iii) outcome validation.

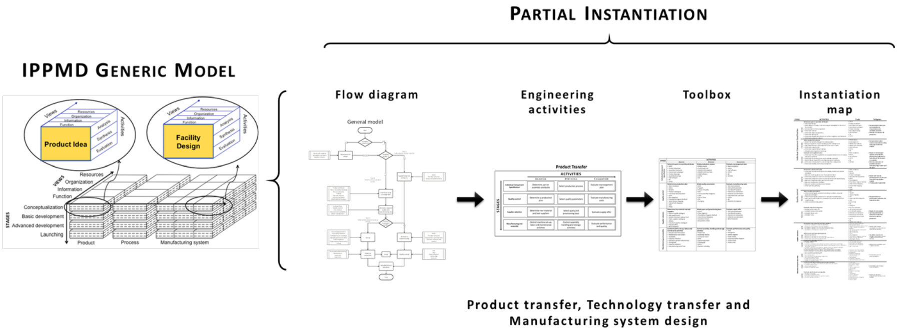

Fig. 1. Methodology to generate partial instances of the IPPMD general model for manufacturing system design.

3 Manufacturing system development instantiation

IPPMD instantiation for manufacturing system development is divided into three categories or subentities that guide the path of development of an MS according to the following characteristics: (i) product transfer when an MS already exists, and a new product is meant to be produced using existing processes in the facilities; (ii) technology transfer when an MS already exists, and a new product is to be manufactured, but new processes must be installed at the plant; and (iii) MS design, when there is the need to create a plant from scratch to allocate the production of a new product.

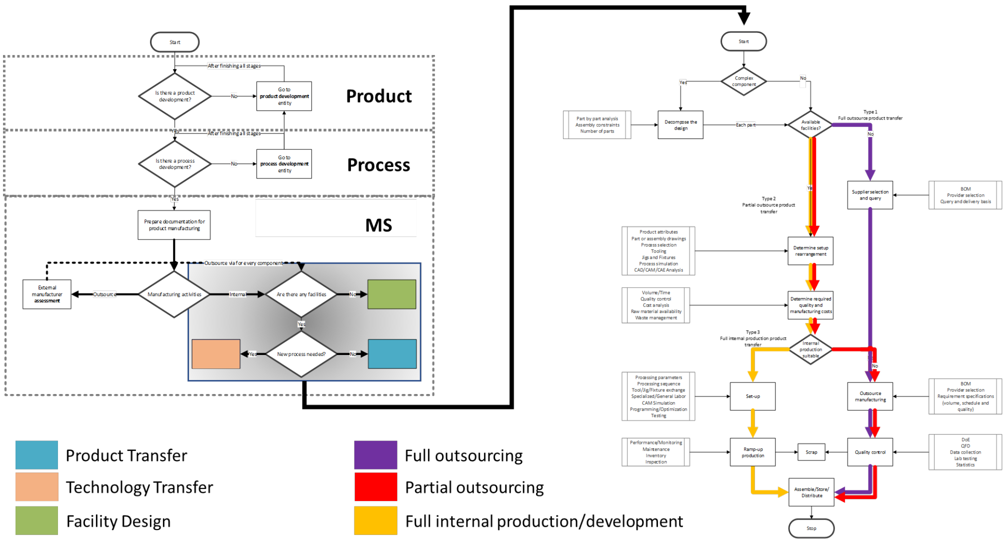

Fig. 2. Partial instantiation flow diagrams

In this way, the methodology elaborates in the development of partial instantiations for each one of the three subentities of the MS development following the structure: (i) flow diagrams, (ii) engineering activities, (iii) toolbox and (iv) instantiation maps (see Figure 1). The first step for instantiation consists of detecting current manufacturing conditions and developing plans for the company. Once product and process entities are completed, documentation is transferred to MS development, where detailed conditions for every case should determine the best route of action aided by decision flow diagrams. Then, each subentity is classified into the following scenarios or types, representing how production will be organised: (i) full outsourcing, (ii) partial outsourcing and (iii) full internal production/development (see Figure 2). These variations go according to the manufacturing company's strategy to create the product, the conditions under which it operates and its core values to understand in detail the series of activities that will be carried out during the instantiation.

The second step consists of structuring engineering activities in four stages that will depend heavily on the previous route selection (see Figure 3a). Each stage is organized in a progressive basis cycle of (i) analysis where data is gathered, (ii) synthesis where vital information is filtered and (iii) evaluation to assess if tollgates are appropriately met. If the results are satisfactory, the project can move to the next stage until completion. Nevertheless, constant iteration and concurrency among stages are needed to include feedback from the system to improve previously designated objectives. This characteristic allows the model to go back and forth between the different points of the instantiated engineering activities.

The toolbox specification is the third essential step of the methodology, allowing each engineering activity to be performed. It is a collection of design, administrative and computer tools that together speed up the progress of activities. The suggested toolbox is a tiny subset of all possible and available existing solutions in the manufacturing industry. Figure 3b, for instance, displays a set of tools applicable to each engineering activity. The toolset availability and definition will depend on the application area and the expertise of the company, and that can be added to the related activity, as some enterprises have their preferred or custom toolset. Although activities are bound to a toolset for structuring reasons, they are not restricted to each paired activity; then, they can be used whether they are available and could prove results in other stages.

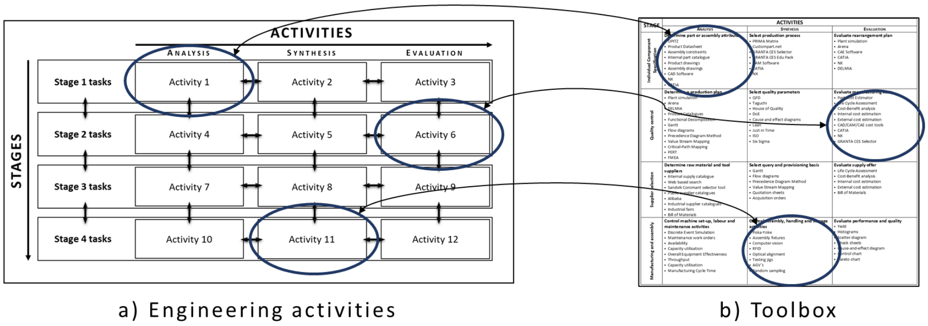

Fig. 3. Partial instantiation engineering activities and toolbox

In order to consolidate engineering activities and toolboxes, maps allow instances of development for any scenario to generate the MS design variant in the final step. The instantiation map lists the series of activities explored in much greater detail and links the tools and tollgates expected by each phase of work. Tollgates are the documentation that allows access to the subsequent activities as they combine the series of data and details that will serve as a starting point to the following stages. The different scenarios ought to have the necessary activities to continue the MS development, but tollgates will indicate whether the activity has been successfully completed or if it is required to elaborate on the stage or the activity. When needed, multiple iterations of stages are necessary to refine the workflow. All in all, the partial instantiation derived following the methodology can be used in a specific design that will generate a particular instantiation ad hoc to the development process.

4 Case studies

In order to test the development potential and advantage of using MS design using IPPMD, partial models were further instantiated to carry out three case studies to assess planning, resource management, and validation of the methodology. Each case study addressed one of the manufacturing criteria with a defined expected outcome (see Figure 4).

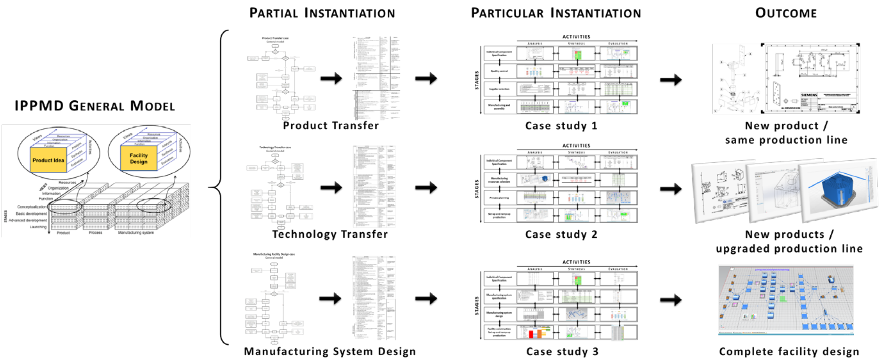

Fig. 4. IPPMD particular instantiations applied in three case studies

4.1 Product transfer

An enterprise specialized in removing processes has a query to produce a thousand pieces per month of a new component that requires precise custom cutting and some counterbored holes. A product transfer case is detected with flow diagrams where just revamping existing processes is necessary to achieve new production goals. As all the manufacturing activities are being carried out within the facility, it was a whole internal production route. Following the partial instantiated model (see Figure 5), it was possible to successfully deploy the production of the new piece by adapting current milling machines to produce the needed amount of production per month.

Stage			Activities	Tools	Tollgates	Project Design Vision Assessment: Results	Effects	Impacts	Benefits
1	Individual Component Specification	Analysis	**Determine part or assembly attributes** • Decompose design, Get datasheets of the components, Determine material, Determine shape and geometry, Determine dimensions	• Product Datasheet • Product drawings	• **Documentation about part and assembly key characteristics and candidate processes**	• Part and assembly key characteristics and **candidate processes** along with machine tool selection and **projected physical rearrangement**	**Business process** • Strategic planning **Machinery and equipment** • More flexibility in the production line **Human capital** • Increased knowledge and experience	**Performance indicators** • Less raw material and parts expenses • Increased running machine hours • Less total machine set-ups	**Strategy** • New product sales • Reduced time for developing new products • Economic feasibility • Order fulfilment improvement • Better process costs • Productivity increase • Quality assurance **Economic** • Higher productivity • Higher sales • Higher value-added for invested capital • New investment feasibility
		Synthesis	**Select production process** • Search the internal catalogue for similar products, Group components or parts matching current machine tools, Map required process and subprocess (from raw to finish)	• PRIMA Matrix • Custompart.net	• **Documentation about machine tool selection along tools, jigs and fixtures needed.**				
		Evaluation	**Evaluate rearrangement plan** • Determine if machine capabilities suit required characteristics of volume, tolerances and finish, Determine if processing times match available machinery	• Plant simulation	• **Report of technological capacity and projected physical rearrangement to manufacture the new part or assembly**				
2	Quality control	Analysis	**Determine a production plan** • Determine a production programme including volume and machine availability	• Value Stream Mapping	• **Report with volume, processing times, routes and manufacturing supplies needed.**	• **Performance** and quality indicators hand by hand with **production data cost analysis reports**	**Organisation structure** • Better procedures and practices • Top-notch manufacturing techniques	**Performance indicators** • On-time supplies • Less WIP inventory • Better manufacturing lead time • Higher % of processing hours	
		Synthesis	**Select quality parameters** • Define internal quality indicators according to volume, scrap and production schedules	• Internal quality policies	• **Documentation on performance indicators and expected quality**				
		Evaluation	**Evaluate manufacturing costs** • Evaluate processing costs, Calculate energy consumption, Calculate labour costs	• Part Cost Estimator • Internal cost estimation	• **Report of cost analysis**				
3	Supplier selection	Analysis	**Determine raw material and tool suppliers** • Search for suppliers in the internal database, Search for internal and external suppliers, Candidate suppliers for internal production route, Candidate a contingency supply route	• Internal supply catalogue • Public supplier catalogues • Alibaba	• **Report with supply candidates for internal and external production**	• Reports and supply **candidates for internal and external production** • Quotation, **ratings** and contracts	**Human capital** • Communication • Decision making • Best practices	**Performance indicators** • On-time supplies • Increase gross profit margin • Reduced manufacturing services	
		Synthesis	**Select query and provisioning basis** • Request quotations, Determine a provision programming, Determine delivery conditions	• Quotation sheets • Acquisition orders	• **Quotation reports and detailed information about suppliers provisioning scheme**				
		Evaluation	**Evaluate supply offer** • Evaluate prices • Evaluate candidates according to previous experience and ratings	• Internal cost estimation • External cost estimation • Bill of Materials	• **Rating documentation and supply contracts**				
4	Manufacturing and assembly	Analysis	**Control machine set-up, labour and maintenance activities** • Set up machine programming, Set up processing sequences, Set up flow lines, Set up buffers and handling equipment, Implement labour shifts, Gather production data	• Discrete Event Simulation	• **Production process documentation**	• Process, assemblies and storage **documentation** • Actual vs expected **performance assessment**	**Business process** • Order fulfilment	**Performance indicators** • On-time deliveries • Fewer downtimes • Reduced scrap and rejection rate	
		Synthesis	**Control assembly, handling and storage activities** • Complete assembly of components and subcomponents, Handle finished parts, Store finished parts, Gather production data	• Discrete Event Simulation	• **Assemblies and storage documentation**				
		Evaluation	**Evaluate performance and quality** • Evaluate production data • Compare performance to expected values	• Discrete Event Simulation	• **Report on actual vs expected performance and quality**				

Fig. 5. Product transfer particular instantiation map

Engineering activities such as evaluate a rearrangement plan, determine a production schedule, quality and costs analysis, along with a correct supplier selection, among others, were used concurrently and iteratively in order to fulfil the production objectives. Furthermore, it allowed to reuse current equipment and apply the already mastered processing capabilities. Some tools used included: datasheets specs, PRIMA matrix, Value Stream Mapping (VSM), Cost estimators, suppliers catalogues and Discrete Event Simulation (DES). The latter was used to model production parameters to assess feasibility for the project as only 10% of the facility's capacity was available. Different scenarios forecasting allowed to reduce bottlenecks to accommodate new production requirements within the capacity of the plant. Project design vision assessment indicated increased strategic planning, more flexibility in the production line, increased knowledge and expertise, and better order fulfilment. It also impacted performance indicators such as increased running machine-hours, better manufacturing lead time, increased gross profit margin and reduced scrap and rejection rate. At the same time, positive strategic benefits went from and increased productivity to new product sales, to say a few.

4.2 Technology transfer

An SME specialising in removing processes was asked to produce a thousand pieces per month of three unique components. One required turning (available in the facility), the other required milling (also available), but the third one was based on plastic extrusion, a process not available so far. Flow diagram assessment detected a technology transfer case. The company decided that it was a unique opportunity to invest in some industrial 3D printing machines as some of their clients were requesting this service. However, production scenario valuation revealed that to achieve the objectives to produce the three new components partial outsourcing route was necessary. Engineering activities included determining part attributes, process selection, determining raw material, machine and tools suppliers, equipment routing and flowlines design, production scheduling and labour evaluation, saying a few. Particular instantiation allowed reusing current equipment while adding a new production line. Some tools used during the development included: OPITZ, CAD/CAM, PRIMA Matrix, cost estimators, bill of materials, process time charts, VSM, and DES. In this case, simulation modelling was used to assess the impact of installing the new production line, the integration of the outsourced parts in the assembly line, process availability times and whether it was justifiable to hire new personnel; thus, forecasting scenarios was necessary to optimise resources in the plant and assist decision making. After project vision assessment, some remarkable effects on the business processes, human and technological capital, and organisation structure were new process development, adapting top-notch manufacturing techniques, adapting to new production lines, and personnel experience gathering. There was also a high impact and improvement in performance indicators such as on-time supplies, better communication and decision making, optimised processes and increased flexibility in the production line. Last but not least, higher sales and higher value-added for invested capital were some of the reported economic benefits, while new product sales and reduced time for developing new products boosted the strategic advantage.

4.3 Manufacturing facility design

This case is about a Mexican manufacturing project focusing on the creation of versatile small-scale CNC machines. So far, the business strategy had been to outsource all manufacturing while engineering centres on the design and assembly of components. However, they had become interested in mounting a small facility for prototyping and testing small batches of their recently designed extrusion module. It included a whole set of processes beneficial for the scope of the project. After following flow diagrams, it became evident that the construction of the entire manufacturing facility could not be affordable due to the expenses of buying equipment. This fact led to a hybrid case where a facility was mounted, and likewise, outsourcing manufacturing was needed due to strategic reasons. Engineering activities focused on two branches. The first three stages allowed to structure the project, mainly relying upon information gathering and projections, then little investment was necessary. The fourth stage is all about plant construction and production ramp-up. As higher investments are necessary, then previous stages had to be thoroughly validated to measure the impact of project tollgates per stage. The toolbox was extensive and included most of the tools used in the other cases. In this regard, DES was a milestone and succeeded in developing the digital model of all the stages while forecasting different scenarios to suit the production target. Computations allowed to determine the best equipment arrangement, labour optimization and machinery expected performance to fulfil the production. The instantiation outcome was the complete facility design (physical and virtual) to master the required processing capabilities of the project and the integration of outsourcing production in the assembly lines. Some remarkable business, human and technological effects using design vision were: projection of capabilities of the production line, better selection of equipment, strategic planning and optimised digital models. At the same time, positive performance indicators included less material and part expenses, less total machine set-ups, on-time supplies, reduced WIP inventory and reduced scrap and rejection rate. At the end of the day, new product sales and new investment feasibility were some strategic benefits, while better process costs, quality assurance and higher value-added for invested capital were some of the economic advantages.

5 Conclusions

IPPMD lightweight framework can be shaped to create partial instantiations that can be used to create particular case studies in different industrial environments. Entities and subentities allow for better classification of manufacturing systems according to the different characteristics, diverse development stages and specific business scopes to set the roadmap and improve strategic planning and resource management. Tollgates deliver qualitative and quantitative parameters to allow performance measurement during the design for outcome validation. Some of the most critical metrics are obtained from DES in the toolbox. It allowed for graphical and numerical interpretation of the complex dynamics and interactions when designing an MS. This powerful tool can forecast different scenarios and design model optimization. Programming the parameters obtained during process design and administrative data using different mathematical approaches expands understanding and sets real-life expectations. Thus, decision making is improved, and better results can be obtained with available resources.

Since necessities from large enterprises are very different to those from SMEs, it would be essential to future-proof the methodology by improving particular instantiations to accommodate a wider variety of manufacturing systems requirements. This strategy will include revising current engineering activities, a more extensive catalogue of the toolboxes and improved tollgates assessment. Furthermore, the inclusion of sensing, smart and sustainable indexes could directly align with current Industry 4.0 modelling trends to cope with increasingly rigid government regulations to include sustainable features spanning the entire product lifecycle.

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