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Conceptual design and simulation of an automotive body shop assembly line

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Abstract: This research work deals with assembly line design and its performance measurement at early stage of a project. The objective is to support decision process on strategical choices regarding the future system configuration. In this perspective, simulation and digital factory concept represent tools and related methodologies to support manufacturing design process, taking into account the whole system lifecycle. However, these model based approaches usually focus on detailed design and less on conceptual design where key decisions are made based on preliminary analysis and usually little available information. In this paper, conceptual models of an assembly line are presented to support the designer's choices and solution analysis. Business process modeling and simulation are explored to address this issue. Several scenarios and preliminary ideas on process layout and structure are evaluated.

Keywords: Conceptual design, modeling, simulation, automotive assembly line, body shop.

1. INTRODUCTION

Nowadays, industrial manufacturers tend to increase variety and mix model to anticipate global market competition. That implies that manufacturing process should be more flexible. However, experience has shown that flexibility has a non-negligible cost and a high initial investment (Biesebroeck, 2007). For instance, the decision to proceed with either a less flexible with low investment process or a flexible one with high investment needs to be supported by performance analysis at preliminary design (Clivillé and Berrah, 2011). In practical, it is difficult and time consuming to perform detailed analysis and quantify the performance gap between several configurations in terms of cost (production loss of earning, workforce saving, set-up time…). Such situation illustrates the need to support decision making based on preliminary performance assessment in addition to investment cost analysis. The objective is to simplify the design process and eliminate non value added activities.

The questions we try to answer are: how to assess several design architectures which can be declined under various configurations? And what are the suitable approaches to handle the complexity of the system? To address this issue we first present the industrial context to describe the involved activities and identify which informations are shared among different actors to run a simulation project. Secondly, main approaches for preliminary system design are presented. The last part of this paper illustrates our approach through an industrial application of an assembly line conceptual design. Finally we discuss about the approach relevance and related research works.

2. CONTEXT AND MOTIVATIONS

In the automotive industry, when a car body is made, the parts are first stamped from rolls of steel, the overall body is welded together to create a shell, and then the individual parts are welded together into the body on a moving assembly line. This part of the process is performed in the Body in White (BIW) workshop. We consider the following level of decomposition to structure our analysis:

- Mainlines or assembly units (ex: opening unit, main floor)
- Subassemblies (ex: front door) supplying the mainline.
- Cells (ex: robotic hemming cell)
- Workstation (ex: manual gun welding)

Digital tools are more and more used to evaluate process planning scenario at preliminary design. However, detailed models from previous projects are needed for new studies. In order to streamline the modeling process, standardized and optimized processes are needed for quick drawing of assembly lines configuration and reactivity in solution performances analysis. The idea is to create predefined generic simulation model which allow testing preliminary ideas to define more detailed and specific models later with less effort.

Besides, design teams find it hard to understand the impact of equipment selection and placement on the factory floor when these activities are expressed in 2D or flows diagram. 3D layout design and enhanced visualization could make it easier to communicate with different disciplines that take part in a new project. Assembly systems design deals with (1) flow or logistics analysis, (2) production throughput simulation, (3) and collaborative design management. In the following section we present related methodologies supporting these activities.

3. ASSEMBLY SYSTEM DESIGN APPROACHES

Classical approaches for production system design are direct assessment, analytical, or by simulation (Fontanilli et al., 2013). The later approach is more interesting for a large amount of data even if it may take too much time to develop. This is because present simulation tools are technical solution oriented (data driven) and not functional oriented (function driven), resulting that detailed information is necessary to perform analysis.

This paper covers specification transformation from production needs (vehicle quantity and mix) to the concept development (ideas and hypothesis on process configuration) which lead to the specification of simulation models. Models are important because they force us to think carefully about the system and help us to develop intuition about its behavior (Hopp and Spearman, 2011). At practical level, all disciplines involved in factory design rely on models to interpret data, predict performance and evaluate action.

In this section, we describe the engineering design process at early stage of an assembly line design project, digital factory tools and methodology, and simulation process.

3.1. Engineering design process

Conceptual design of an assembly line consists in (1) physical layout and workstation organization definition, (2) flow analysis, (3) resource dimensioning and (4) sourcing strategy definition. These activities can be commonly supported by generic simulation model based on previous projects known as standard processes.

Choices made by designers at the preliminary design affect 60% of all the system lifecycle costs (Feng, 2005) (design, set up, start up, ramp up, constant capacity, production decline, dismantling). They are usually limited by the initial hypothesis they made. That's why the choices made at preliminary design may introduce some constraints to future optimizations on the assembly line. To streamline these activities information technology and digital tools are introduced below.

3.2. Digital factory tools and methodology

To support and improve the design process, digital factory concepts and associated methodologies have been explored. It is a technology to capture and represent information to model manufacturing systems and available processes in a factory, usually for performance analysis purpose (Kühn, 2006). It represents the backbone which handles the factory resource and process information. It is also a part of product lifecycle management solutions that integrate several tools to process information such as flow simulation data, component library, process planning, and layout design. Indeed, each expert is using the application that is most suited for their activities. In the literature, many research works deal with technological point of view of digital factory (Chryssolouris et al., 2009) but few on functional aspects for performance analysis.

Assembly systems design and planning relates to acquiring product data, establishing tool and process libraries from a resource database, optimizing layout parts flow, defining the assembly process (Gregor and Medvecky, 2010). This is supported by simulation, a main compound of digital factory.

3.3. Simulation in the context of digital factory

Simulation is an experimentation with a simple computer imitation of an operating system as it would progress through time, for the purpose of better understanding and/or improving that system (Robinson et al., 2012).

Five steps are usually identified in an automotive body shop assembly line: conceptual design, detailed design, launching phase, ramp-up and fully operational phase. In the conceptual phase, new methods of manufacturing and material handling are tested by the engineers. At this point, general specifications of the line are drawn based on rough planning. This is transformed into computer simulation model for detailed analysis.

In many cases simulation models are just for one purpose and are rarely reused after the initial simulation study has been completed. The successful use of long-life-cycle simulation models is one of the challenges in engineering design. The following section present some best practices in the context of conceptual design and commonly used simulation techniques.

4. MODELING TECHNIQUES FOR SIMULATION

Preliminary factory design and planning lack of reliable input data for simulation and performance analysis. The success of a simulation project requires adequate engineering techniques such as conceptualization, hierarchical modeling, modular design or functional simulation which are detailed below. These approaches are essential to support ideas generation (brainstorming) and performance analysis (Simulation).

4.1. Conceptual modeling and abstraction

Conceptualization consists in simplifying and using idealized models of the system (Figure 1). Conceptual model is the most important aspect of the simulation modeling process. Indeed, conceptualizations at early stage of the design process allow decision makers to consider a large number of possibilities. This phase is less formalized than the detailed one (Geiskopf, 2004) and requires high integration of all discipline (people, objects, knowledge) which imply highly concurrent and collaborative engineering process.. Figure 1 shows four steps of simulation process cycle.

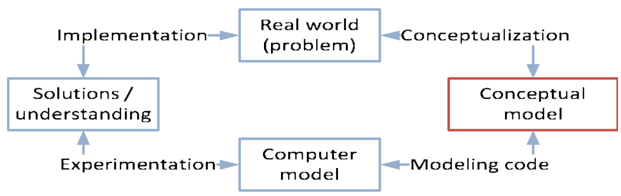

Figure 1 - Modeling process for simulation (Robinson et al., 2012)

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A conceptual model is a non-software specific description of the computer simulation model, describing the objectives, input, output, content and simplification of the model (Onggo and Karpat, 2011). Identified parameters at a higher level process become a lower level constraint for decision making. For instance, production rate is an input data for process planners as stock level are for layout planners, while resulting throughput and cycle time are input for process designers.

4.2. Hierarchical modeling

In a simulation project, hierarchical structure is managed by modeling together all objects in the same level of analysis. This can be done by arranging at the factory level, assembly units and subassembly lines (section 2). As we move forward in the design process, detailed level of each subassembly is more precisely defined. In the context of factory design, bloc layout is first defined to place the assembly units according to effective logistical flow. Each subassembly line needs to conform to this generic layout. Only a few commercial off the shelve simulation tools allow effective management between different levels of analysis.

4.3. Modular design

Another important aspect of assembly systems design is its modular feature. Modular design is the concept of pre-combining a large number of components into modules to the main assembly line through simple and standardized procedures. This approach improves the robustness of the system by limiting the impact of disruptions (product, volume or mix model change) on overall performance (Schuh and Brussel, 2003). This has been demonstrated by decoupling the influence of design parameters on key performances.

An example of modular assembly line contains a part loading module, a welding module and a flexible part conveying system. The welding module may include several spot welding and handling robots that can be also declined into several configuration.

The art of modeling is in the selection of the proper compound model for a given situation and the coordination of various models used to assist the decision making process (Hopp and Spearman, 2011). Most simulation tools propose components oriented modules rather than domain-oriented (e.g. a transfer system model rather than a conveyor or a handling system). Modular assembly design approach leads to solution focused and not component focused which is more flexible and reusable. This is because these patterns are domain dependent and are intended for regular specific use.

4.4. Functional simulation

This last approach considers the functional aspect from the system rather than the structural point of view of the CIMOSA framework (Computer Integrated Manufacturing Open System Architecture) (Vernadat, 1999). It is a kind of extension and mix between hierarchical and modular concepts. The focus is on design options or functions (Pierreval and Paris, 2001) rather than design parameters (George Michalos, 2011) for a simulation based system configuration. Most simulation tools are technical solution modeling oriented and dismiss functional aspects that can be implemented by several possible solutions. The limitations of this approach are shown to be determined by the capabilities of modeling and simulation tools (Pierreval and Paris, 2001).

Since technological advances in digital factory concepts have been made, the gap between industrial practices and research needs to be reduced by making these technological advances closer to engineering designers.

The solution to this issue from functional simulation point of view is to model as generic possible model to suit several configurations such as the ability to change between two types of transfer system between assembly units.

Considering different simulation techniques, the functional, informational and organizational point of view are represented. Preliminary assembly system design and planning activities need shared representation for all disciplines to evaluate the impact of technical solution they are implementing (layout, process plan, logistical).

We base our research hypothesis on previously presented simulation modeling techniques. And show through case study how preliminary design choice and analysis impacts the final configuration of an assembly line.

5. ASSEMBLY SYSTEMS CONCEPTUAL DESIGN

The conceptual phase of an assembly system design refers to the initial stage where assembly methods and material handling are tested. In this section, we describe a simulation modeling approach and illustrate each step by a simple pull flow control of an assembly line. The five steps below summarize the preliminary analysis steps for an assembly line conceptual design. Some are based on design approaches presented in previous section.

1. **System description**: a brief description of the problem and situation from the real world (Figure 1).
2. **Preliminary analysis**: define manipulated artifacts and assembly system data.
3. **Conceptual modeling**: structure macro process and put logical links of physical and informational flows using bloc diagram. Compare several structure of the process.
4. **Detailed design**: Identify potential configurations for the identified architecture and define a computer based implementation of each configuration.
5. **Simulation**: debugging and running simulations to assess key performances indicators identified at step 2.

Several types of models are needed to deal with various assembly line architectures. These models enable decision makers to formalize the validation phase of each design step. For instance, requirement specifications require functional need validation and architectural specifications require physical validation (Referring to the V cycle of design process). This is why preliminary and detailed phase should be distinguished and more effort should be brought to the preliminary one.

Figure 2 shows that the choice on architecture line can lead to several configurations and predefines its performance level. We underline that a "configuration" is a set of value of design parameters (e.g. flow control, automation level) and a combination of assigned resources types to each subassembly.

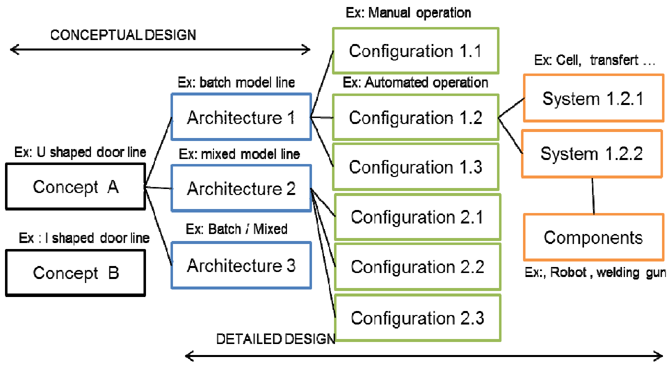

Figure 2 - Set of solutions for conceptual and detailed design

Our previous research work in this topic presented the industrial issue (Feno et al., 2013) and a global approach based on three assumptions: (1) solution analysis and identification of potential process configuration based on designers collaboration, (2) simulation model for experimentation using discrete event paradigm and (3) multi criteria analysis based on AHP (Analytic Hierarchy Process) (Saaty, 2000). Here, we focus on the second point, which is the specification of simulation models, as the main criteria for decision making have been already identified.

5.1. System description

The automotive body shop assembly line is divided into a number of sub-processes which include doors that goes to the body openings. The opening door assembly process contains both manual and automated subassemblies from the sheet metal part warehouse to the painting shop.

- A manual assembly preparation with 6 main operations: to assemble together an inner panel and an outer panel with their belt reinforcements, crash bar, and hinge pillar.
- An automated hemming to assemble the inner and outer subassemblies in one assembly product.
- A metal line where several opening parts are assembled with the main car body

Buffers, which size and type depend on cycle time and flow control, can be inserted between the sub-processes.

5.2. Preliminary analysis

According to the number of models to produce on the line, a flow control is needed to fulfill the metal line specific demand which is a known sequence of vehicle. At this point, three pull assembly systems are possible (Figure 3):

a) A single part flow according to production sequence
b) A batch flow with constant work in process
c) A batch flow control with kanban system

Many academic research works have issued this problem and showed that a constant work in process with the appropriate batch size is a good compromise between several flow control (Hopp and Spearman, 2011). Generalized laws have been expressed since then. In stations with batch operations or with significant changeover times:

- The minimum process batch size that yields a stable system may be greater than one.
- As process batch size becomes large, cycle time grows proportionally with batch size.
- Cycle time at the station will be minimized for some process batch size, which may be greater than one.

This is a starting point for conceptual modeling. As for us, the issue is to break down the preliminary design process from production specification to architectures and configuration of the assembly line. A simplified representation of data defining the system is then required. The model is intended to support communication between designers and simulation analyst.

5.3. Conceptual modeling

This step involves a simplified model of each type of process and representation of manipulated information to specify the assembly line. Two types of information are identified from this modeling approach: Operating mode and buffer type. Single part flow (a) uses less buffer space but has a lower throughput rate considering an important setup time between models. Batch flows (b and c) show a high throughput rate but uses more buffer space.

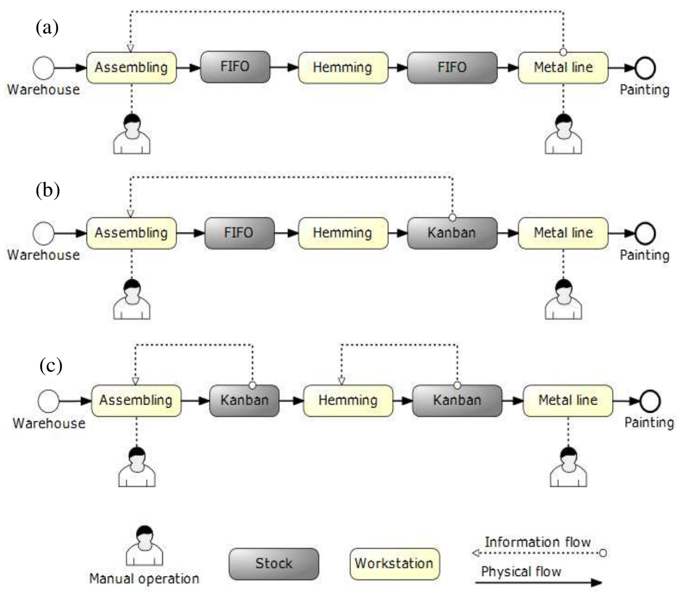

Figure 3 - Conceptual model of the assembly line

Considering a high mixed model production demand with a significant set up time and a high throughput rate, the architecture (b) is relevant to fulfill the production.

5.4. Detailed design

The detailed design phase refers to the stage where detailed layout and equipment specifications are verified for the system. While detailing the second architecture (b) with necessary workstations, several configurations are possible according to layout constraints. A U and I shaped assembly configurations are identified as described in Figure 4.

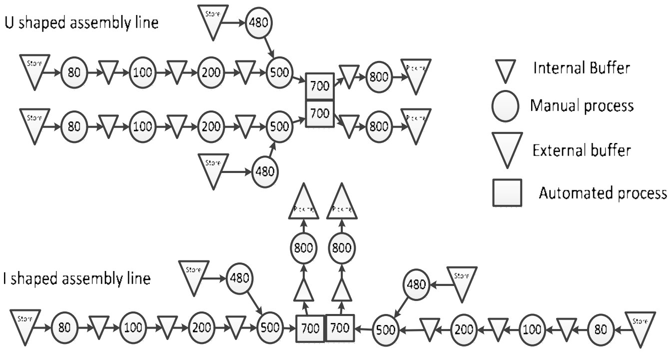

Figure 4 - Detailed design of scenario (a)

The idea is to compare both configurations based on flow, surface, and resources utilization which are interconnected. Below, we have a list of the main key performance indicators to measure assembly line configurations efficiency:

- Process capacity – the capacity of the process; maximum output rate, which is measured by dividing unit produced by unit output.
- Throughput (flow rate) – average rate of flow for a given point.
- Capacity utilization – percentage capacity being used.
- Availability – degree to which the system is operable.
- Cycle time (or floor-to-floor time) – time between successive units, as they are output from the process.
- Lead-time (flow time) – average rate that a unit requires flow through the process form entry to exit point.
- Work in process (WIP) – material that has entered the production process but is not yet a finished product.

Other criteria such as investment, required area, logistical efficiency and flexibility are necessary to complete the analysis. Flexibility is one of the design objectives here. There are many forms of flexibility in assembly systems:

- Product flexibility: produce different product in the same assembly line.
- Volume flexibility: produce at different production rates without increasing exploitation cost.
- Mix model flexibility: adapt percentage of different models mix in the same assembly line.

To deal with volume flexibility in a manual assembly line, operators need to be able to move from a station to another. In U the shape, operators can be added or removed to match the demand takt time. The first configuration (U) allows this flexibility unlike the second one (I). In other words worker positions are fixed in I shape while they can move in U shape due to the reduced layout distance between workstations. That brings flexibility to the assembly line in case of lower production volume. A simulation analysis is performed to support this statement and measure key performances.

5.5. Simulation and performance analysis

Identified configurations in Figure 4 were modeled with *Plant simulation*, one of the digital factory Tecnomatix solutions of Siemens and *Witness* from Lanner group. At first sight, there is no difference between U and I shape assembly in terms of throughput considering the same cycle time at each workstation. But workforce requirement has been investigated using a design of experiment analysis. The U shaped assembly line seems to require less resource in case of low demand.

There is also a gap between conceptual and detailed performance analysis in terms of throughput and availability. Conceptual analysis is based on previous referenced project while detailed analysis is based on actual project values.

Preliminary performance in most case is lower than expected, this is justified by the modification of the initial process due to factory new constraints or product specifications change. In response, engineers naturally increase the capacity of their process perimeter. The risk in preliminary assessment is to specify an assembly line with a lower capacity than expected or an overinvested factory.

6. DISCUSSIONS

By breaking down the modeling process into five basic steps we have been able discuss and illustrate the decision making process for assembly systems design and reconfiguration.

Related works about conceptual simulation modeling have been undertaken in several contexts. Some researchers used simulation and lean approaches in the healthcare clinic service (Robinson, 2012). Lean manufacturing techniques involving the business process participants has been used as a guideline for simulation model specification. Others have combined business process modeling (BPMN) and simulation in logistics for cosmetic industry (Fontanilli et al., 2013). All of these approaches intend to analyze first the process in order to identify inefficient tasks, to spot possible effectiveness improvement and understand where value can be added. Our approach rather focuses on the preliminary analysis phase that we applied on internal logistic automotive assembly system.

The relevance of such approach is revealed while addressing the need for a shared and standardized model to describe the rough process requirements. It is though limited by the formalism of the business process language. In practical, conceptual models, called “synoptic” are drawn from scratch with illustrated objects representing each component or set of components of the assembly line. Comparing several documents that have been exchanged between simulation analysts and process engineers, we have noticed the following:

- Each conceptual model is different and uses customized representation of modeling objects.
- Main part of the exchanges is about flow control of lines.

- Interviews reveal lack of data at this step of the process.

Common tread between several approaches presented in this paper demonstrate the need to improve communication and collaboration between assembly systems modeling stake holders such as process engineers and simulation analysts.

7. CONCLUSIONS AND PROSPECTS

The objective of this paper is to present a conceptual design approach to explore ideas and perform early analyses in assembly design and planning. In practice, there is a lack of verification and validation methods to support this phase. Usual modeling approaches for simulation focus on detailed design and less on conceptual design where key decisions are made. As the design matures, identified issues were used as a basis for more detailed analysis.

For that, we presented relevant technics for an efficient simulation modeling process (modular, hierarchical and functional). We showed through a case study the importance of preliminary analysis towards the assembly line architectural decisions to make before performing detailed design and simulation. An experimental gap between conceptual and detailed design from automotive body shop assembly lines have been highlighted afterwards.

Early design decisions typically lack formal preliminary analysis. At strategic level, economic criteria are more important. In practice, experience based rules are often used for decision making when facing incomplete or unreliable information. One of the future work directions is to establish relationships between economic and technical criteria.

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