Manufacturing System Flexibility: Sequence Flexibility Assessment
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Abstract

Manufacturing industry is facing new challenges in a competitive and constantly changing environment, with growing complexity and high levels of customization. Mass customization caused that product variety increased drastically and affects production system flexibility. System flexibility is the ability of the system to cope with product variety. Based on industrial experience, the production system may be represented by three main elements, which are products, processes and resources. This paper, which is a part of an overall research work, studies the products - processes interaction. This interaction investigates the ability of the processes to manage existing and potential product variety. Based on a set of constraints, which are used to build sequences, an indicator is introduced to provide decision support capabilities to guide the changes to perform in the production system for better sequence flexibility. Experimental results from the automotive industry are presented.

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Keywords: Manufacturing system; Flexibility; Sequences; Product variety

1. Introduction

For many decades, cost and production rates were the most important performance criteria in manufacturing, and manufacturers relied on dedicated mass production systems in order to achieve economies of scale. Nowadays, manufacturing organizations understand that these criteria have been diversified. The competition has increased and the customer base is more mature. This makes flexibility an increasingly important attribute to Manufacturing.

Modern manufacturing systems are facing continuous changes in the environment they operate. These changes include the rapid introduction of new products, abrupt changes in product demand and more frequent modifications to existing products. Many academic publications have pointed out that the quantification of flexibility is difficult to be handled and mostly limited to special cases (Tolio, 2008). These difficulties lay in some flexibility characteristics, such as its property of being potential and its inherent multi-dimensionality (Sethi, et al., 1990).

In (Chryssolouris, et al., 2013), flexibility is defined as “the sensitivity of a manufacturing system to changes. The more flexible a system, the less sensitive to changes occurring to its environment it is”. Our approach consists on modelling flexibility on three main forms which are configuration flexibility (LAFOU, et al., 2015), interfaces flexibility (LAFOU, et al., 2014) and sequence flexibility. This research work will focus on sequence flexibility assessment. Sequence flexibility, can be defined as the ability of a manufacturing system to master a variety of sequences in order to cope with product variety. It has been shown in (Azab, el al., 2007) (Koren, 2010) that the sequence flexibility is an important aspect of manufacturing system performance. Nevertheless, in order for flexibility to be considered in the design and operation phase, it should be defined in quantifiable terms.

A key research question asks what factors enable better systems sequence flexibility control, in order to be rapidly adjustable to current market fluctuations. And how can those factors are used so that designers can compare multiple mixed model assembly line sequences and identify the best
alternative.

In order to build some responses to these interrogations, an overview of the existing sequence flexibility measures is primarily presented. Then, a detailed description of our approach is introduced as well as the results of its application to an automotive industry case.

2. Framework and motivation

In the mixed model assembly line, the assembly sequence plays a key role in determining the quality of the assembled product, as well as assembly process design issues. The challenge is to find the right sequence flexibility to cope with the exiting product variety, and that could be adjustable for potential variants with minimum modification and consequently with less cost and time.

Several methods are available to represent the relationship among component parts in an assembly. One of the commonly used assembly representation is assembly operation precedence graph (Fig.1).

It is a graphical network wherein nodes represent mostly the assembly operations and the lines between nodes the precedence relations. The assembly task precedence graph is useful to generate all feasible assembly sequences. Most precedence graphs use assembly tasks rather than components, but if a base component is first established, then the operation of adding each subsequent component can simply be represented by the component on the precedence graph (Hu, et al., 2011).

An assembly sequence is defined as the set of operations required to assemble a given product. Different sequences may co-exist in a same assembly line in order to deal with product variety. An assembly sequence is composed of a set of operations which is common to all the variants (as illustrated in Fig. 1 by the operations 1,2,3,4 and 7), and a set of operations which is specific to a given variant (The operation 8 of variant (c), in fig.1).

Some operations have flexibility to be processed before or after each other or could be done simultaneously (for example, operations 3, 4 and 5 in fig. 1), which makes sequence flexibility management more complex. Consequently, in addition to precedence constraints, complementary studies should be conducted in order to identify additional considerations to build a robust indicator to sequence flexibility assessment in order to be as close as possible to real industry conditions.

This paper investigates the importance of designing flexible sequences and identifies the constraints that should be considered to evaluate sequence flexibility and compare different mixed model assembly lines, in which a new variant is candidate to be introduced.

3. Related work

3.1. Product variety management and sequence commonality

Effective management of product variety can provide important competitive advantages for a company. However, it is a challenge of manufacturing to produce variety of products with limited resources. There are various strategies that suggest several methods for variety management; these methods are well known in industries. In fact, to handle variety, manufacturers use several product design methods, including product family development (Du, et al., 2001) and parts commonality (Koren, 2010).

Usually the product specifications are the ones that define the sequence of operations carried out on the product. In order to accommodate the increasing product variety, developing product families has been recognized as an effective means to achieve the economy of scale (the same basic components are used across different products of the family). Through product family organization, sequence commonality could be increased and then the introduction cost of a new variant minimized.

In fact, the same logic is used in building assembly sequences, in which a common sequence may be dedicated to common components and specific operations are included.
in order to maintain the level of differentiation needed. However, as products and their variants evolve and change over time, the boundaries of product families change as well. Consequently, similarities between product family members are reduced, which makes sequences variety management more complex.

3.2. Sequence flexibility measures

The keywords used in the literature, which are closest in their utilization to the description of our problematic regarding sequence flexibility, are process planning and process flexibility. Process planning is defined, by (ElMaraghy, et al., 2013), as the link between product design and product manufacturing and re-manufacturing. Process planning is part of the “soft” or “logical” enablers of change in manufacturing. It connects product design with product manufacturing and production as well as manufacturing system design. In (Azab, et al., 2007), a new method of reconfiguring of an existing “process planning” of a machining system when introducing a new variant is presented. The concept used in their method called “Reconfigurable Process Planning (RPP)” proposes to reduce the sequencing problem to a problem of integration. The objective is to determine the best location to insert the new operation in the existing sequence while optimizing objective criteria and without violating some specified constraints. A Reconfiguration Index is proposed to measure the percentage of change, i.e. reconfiguration of the original master process plan due to the additional inserted features.

Process flexibility, in turn, is introduced in (Sethi, et al., 1990). It reflects the diversity of parts that a production system can produce without major modifications. One measurement would be the volume of the set of part types that the system can produce without major setups. (Warnecke, et al. 1982) measure it by the changeover cost between known production tasks within the current production program. (Son, et al. 1987) measure it by the ratio of the total output and the waiting cost of parts processed for a given period.

For the same purpose, some scientists used the similarity coefficients in order to assess operations similarity. The most common and well-known similarity coefficient in the literature, regarding operations similarity, is Jaccard’s similarity coefficient introduced by (McAuley, 1972):

\[ JSC_{xy} = \frac{a}{a + b + c} \quad ; \quad 0 \leq JSC_{xy} \leq 1 \]  

In Eq. (1), \( JSC_{xy} \) is the Jaccard’s similarity coefficient between Variants \( x \) and \( y \); \( a \) is the number of common operations between Variants \( x \) and \( y \); \( b \) is the number of operations in Variant \( x \) but not in Variant \( y \); and \( c \) is the number of operations in Variant \( y \) but not in Variant \( x \).

Weighted similarity coefficient is a logical extension or expansion of the binary data based similarity coefficient (Yin, 2006). Recently, an extension to Jaccard’s similarity coefficient is introduced in (Navaei, et al., 2016). It considers the importance weight for each individual operation. In this case, Eq. (1) is modified as follows:

\[ JSC'_{xy} = \frac{\sum_{k=1}^{T} w_{k} x_{yk} f_{jk}}{\sum_{k=1}^{T} w_{k} x_{yk}} \quad ; \quad 0 \leq JSC'_{xy} \leq 1 \]  

Where

\[ I_{xk} = \begin{cases} 1 & \text{if variant } x \text{ requires Operation } k \\ 0 & \text{Otherwise} \end{cases} \]

\[ I_{yk} = \begin{cases} 1 & \text{if at least one of variant } x \text{ or } y \text{ requires Operation } k \\ 0 & \text{Otherwise} \end{cases} \]

\( T \) is the total number of operations among the variants and \( W_k \) is the weight of Operation \( k \).

Based on the aforementioned scientific literature and on the industrial practice in automotive assembly plants, we define sequence flexibility as the system’s ability to cope with variety of products requiring different sequences, on the same production line, with the least time and cost. We propose to deal with this issue by two different ways. Firstly, an indicator for sequence flexibility is introduced using the specificity of product family, by incorporating additional constraints in order to approximate the real context that is facing industrials in the assembly lines. Secondly, the weight factor \( W_k \), proposed in (Navaei, et al., 2016), is detailed based on the same aforementioned constraints. The Jaccard’s similarity coefficient is applied in its weighted form. The obtained results of both methods are compared.

4. The proposed approach

4.1. Problematic presentation

An assembly sequence is the sequence of operations required to assemble a product. An alternative sequence may be obtained by either an interchange or a substitution of certain operations by others. Consequently, multiple sequences co-exist in the same assembly line in mixed model assembly lines.

In automotive industry, designers define a reference assembly graph when designing plants, this graph is equivalent to the master process plan mentioned in (Azab, et al., 2007). Product designers have also to consider it in the design of new variants. Nevertheless, assembly reference graph changes over time with the advent of new technology, regulations, etc. Therefore, several plants of one company may not comply with its reference assembly graph. Moreover, due to the new strategy adopted by vehicle manufacturers, concerning sharing resources, it is becoming increasingly difficult to converge to one assembly reference graph, because each industrial tries to defend its own assembly graph. Consequently, the convergence to a unique
assembly graph requires a period of transition and it is not easy to implement.

In this context, in order to evaluate sequence flexibility, the idea is to confront the assembly graph of the new variant to the existing assembly line.

When introducing a new variant, several cases arise as presented below, in table 1, where 1 means comply with and 0 not comply with:

<table>
<thead>
<tr>
<th>New variant</th>
<th>Assembly reference graph</th>
<th>Existing line</th>
</tr>
</thead>
<tbody>
<tr>
<td>- case 1-</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>- case 2-</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>- case 3-</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>- case 4-</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 1. Possible scenario when a new product variant is introduced

In case 1, sequence flexibility is maximal because no modification in the line is required. In the second case, the new variant will logically be easily introduced in the existing line. However, it depends on the company strategy, if it is giving priority to the conformity with the assembly reference graph or to the time to market of the new variant. Consequently, we are concerned with the two last cases in which the new variant could not be launched without modification in the assembly line.

4.2. Approach description

Based in the industrial practices in an automotive assembly line, a number of additional constraints are identified in order to complete the precedence constraints. It should be noted that this list is not exhaustive. The identified constraints are:

- Ergonomic constraint
- Component availability constraint
- Tool availability constraint
- Handling availability constraint

An example is presented below in order to illustrate each constraint. The tank assembly is the operation considered. Most vehicles are concerned with this operation. However, the component tank may have several varieties that form the tank family component. Then, the component tank may be considered as a specific component for a given new vehicle and consequently, as a specific operation.

Depending on the vehicle variant, the tank may be assembled in the underbody of the vehicle or in the vehicle trunk. In this case arise an ergonomic constraint, due to the position of the car body while the assembly operation is performed as illustrated in Fig.2.

Furthermore, an additional constraint may arise, which is the component availability constraint, due to the logistical flow of the component; the tank is a voluminous component and its delivery to the line requires a specific provision. If the vehicle variant requires a specific tank, a tool availability constraint may concern the need of different clamping specifications. Finally, a handling availability constraint corresponds, for example, to a manipulator that is not necessarily available at the novel assembly location.

While introducing a new variant in an existing assembly line, the first verification that is systematically done is the number of common components. If the new variant has identical components as those that are assembled in the existing assembly line, the variant can be easily introduced and assembled. Because it will have an assembly sequence that may easily be absorbed by the existing assembly sequence. Otherwise, if the new variant requires specific components, further verification should be done in order to assess its sequence flexibility based on the number of verified constraints. If we make the same reasoning in terms of operations, e.g. increasing common operation increases sequence flexibility, it will not be always true due to the constraints of specific operations as illustrated in the aforementioned example of the tank assembly. One solution to this problematic is to introduce a weighting factor in order to classify the importance of each operation. In our case, the weighted Jaccard’s similarity coefficient, $J_{SC}$, is a suitable indicator because it is pointing out the impact of specific operations. The weighting factors will be computed using the constraints identified above.

4.3. Mathematical formulation

Let $l$ be a subsection from the assembly line.

$l$ represents as well the assembly sequence which covers all the existing assembly sequences in the subsection.

$R$ represents the set of components of product variant $x$

$S$ represents the set of components assembled in subsection $l$
of the existing line. 

\( F_{s,l} \) is sequence flexibility indicator if variant \( x \) is introduced in assembly subsection \( l \)

Let \( i \) be the component variant

\( z \) the number of components of the product variant \( x \)

\( q \) the number of specific components

\( t \) the number of common components

Let \( n_i \) be the number of verified constraints of component \( i \) and \( m_i \) be the total number of constraints considered for component \( i \).

A component variant corresponds to an operation.

Identical volume of production is considered.

1) If \( R \subset S \Rightarrow F_{s,l} = 100\% \)

2) If a specific component of variant \( x \) is identified, the following constraints should be verified:
   - Precedence constraint
   - Ergonomic constraint
   - Component availability constraint
   - Tool availability constraint
   - Handling availability constraint

The proposed sequence flexibility indicator is introduced as follows:

\[
F_{s,l} = \frac{\sum_{i=1}^{z} n_i}{\sum_{i=1}^{z} m_i} ; \quad 0 \leq F_{s,l} \leq 1
\]  

(3)

3) If a specific component variant is identified, it corresponds to a specific operation. One proposition consists on computing the Jaccard’s similarity coefficient, introduced in (Navaei, et al., 2016), between the two variants, \( x \) and \( l \).

\[
JS'C_{xl}' = \frac{\sum_{i=1}^{z} W_i l_{xi} l_{yi}}{\sum_{i=1}^{z} W_i l_{xyi}} ; \quad 0 \leq JS'C_{xl}' \leq 1
\]  

(4)

Where

\[ l_{xi} = \begin{cases} 1 & \text{if variant } x \text{ requires Operation } i \\ 0 & \text{Otherwise} \end{cases} \]

\[ l_{xli} = \begin{cases} 1 & \text{if at least one of variant } x \text{ or } l \text{ requires Operation } i \\ 0 & \text{Otherwise} \end{cases} \]

\[ W_i = \begin{cases} \frac{\sum_{j=1}^{q} (m_i - n_j) + \sum_{i=1}^{t} n_i}{\sum_{j=1}^{q} (m_i - n_j) + \sum_{i=1}^{t} n_i} & \text{if } i \text{ is a common operation} \\ \frac{\sum_{j=1}^{q} (m_i - n_j) + \sum_{i=1}^{t} n_i}{\sum_{j=1}^{q} (m_i - n_j) + \sum_{i=1}^{t} n_i} & \text{if } i \text{ is a specific operation} \end{cases} \]

5. Application

In this section, we experiment the sequence flexibility model, presented above, in two automotive industry plants where are commonly assembled several vehicle variants. We consider that a new vehicle variant, \( x \), is candidate to be assembled in both of the mentioned plants, as showed in fig. 3.

![Fig. 3. Case study description](image)

Sequence flexibility analysis are performed in order to identify the plant which is able to accommodate the new variant with minor modifications in its existing assembly sequence.

The subsection considered in both of the line concerns the assembly of the under-body structure. Five major component families are selected. A detailed description of the case study is given in table 2.

- \( C_i \) is the component family of component \( i \).

- The columns, Line a and Line b, give information about if the new component is common (Ok) or specific (Nok).

- \( (n_i)_{xl} \) is the number of verified constraints of component (operation) \( i \) of variant \( x \) while introducing in line a.

- \( W_{ia} \) is the weighting factor of component (operation) \( i \) while introducing in line a.

<table>
<thead>
<tr>
<th>Line a</th>
<th>Line b</th>
<th>((n_i)_{xa})</th>
<th>((n_i)_{xb})</th>
<th>(W_{ia})</th>
<th>(W_{ib})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(C_1)</td>
<td>Ok</td>
<td>5</td>
<td>5</td>
<td>0.28</td>
<td>0.23</td>
</tr>
<tr>
<td>(C_2)</td>
<td>Ok</td>
<td>3</td>
<td>5</td>
<td>0.11</td>
<td>0.23</td>
</tr>
<tr>
<td>(C_3)</td>
<td>Nok</td>
<td>5</td>
<td>1</td>
<td>0.28</td>
<td>0.18</td>
</tr>
<tr>
<td>(C_4)</td>
<td>Ok</td>
<td>5</td>
<td>2</td>
<td>0.28</td>
<td>0.13</td>
</tr>
<tr>
<td>(C_5)</td>
<td>Ok</td>
<td>4</td>
<td>5</td>
<td>0.05</td>
<td>0.23</td>
</tr>
</tbody>
</table>

\( F_{s,a} = 88\% \)

\( F_{s,b} = 72\% \)

\( JSC'_{a,x}' = 84\% \)

\( JSC'_{b,x}' = 69\% \)

Table 1. The study case description

6. Discussion

The introduction of a new variant constitutes a disruptive element for the existing assembly sequence. Its ability to accommodate this variety traduces its sequence flexibility degree. The proposed list of constraints enable to quantify
the behaviour of the assembly line regarding the new component.

Therefore, the introduction of variant x requires two new components in both of lines a and b. Consequently, the $JSC_{xy}$ introduced in eq. (1) gives the same value for both of the line. Because only the specific character of the operation is considered.

$$JSC_{xa} = JSC_{xb} = 60\%$$

For instance, using a weighting coefficient enables to get additional considerations. Both of the methods enable to select the line a, as the better alternative in which the product variant x will be easily introduced:

$$F_{s,a} > F_{s,b}$$

$$JSC_{ax}' > JSC_{bx}'$$

7. Conclusions and perspectives

In the present paper, a sequence flexibility indicator is proposed, which is a part of an overall research work introduced in (LAFOU, et al., 2015) (LAFOU, et al., 2014). Based on industrial practices, a list of assembly constraints is established and developed to weight a functioning factor for the Jaccard’s similarity coefficient. Both of the methods are applied to an automotive case study; the obtained results are in good agreement. More extensive studies should be conducted in order to point out additional ameliorations.

The first experimental results showed the relevance of this indicator to help product and manufacturing systems designers to take the right decisions to ensure an optimal sequence flexibility for their manufacturing system.

Future work should incorporate a further and more detailed analysis of the financial aspect for the final decision. Some of future research work opportunities in this area are highlighted below:

- Sequence flexibility is a very useful practice to cope with product variety. However, sensitivity analysis should be performed for the proposed mathematical models in order to test the robustness of the obtained results and increase the understanding of the relationships between the identified constraints.

- Integrating more criteria in the sequence flexibility assessment, such as the production volume and the geographical considerations, enables better modelling of sequence flexibility issue.

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