AN ASSEMBLY-ORIENTED PRODUCT DESIGN METHODOLOGY TO DEVELOP SIMILAR ASSEMBLY OPERATIONS IN A MIXED-PRODUCT ASSEMBLY LINE

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Abstract

With the growing demands for product variety, Mixed-Product Assembly Lines (MPALs) as an effective means of creating product variety are recently increasing in manufacturing companies. However, handling different products from distinct product families creates high complexity in performing assembly operations in an MPAL. The elevated complexity, calls for increased similarity between assembly operations in an MPAL which requires product design changes accordingly. Hence, the objective of this paper is to suggest an assembly-oriented product design methodology to increase similar assembly operations for various products cross-product families. The proposed methodology uses Interface Diagram, a product architecture modelling tool, for comparing assembly operations cross-product families, suggesting an assembly-oriented design, and communicating it to designers. The methodology has been developed by conducting a case study in heavy vehicle manufacturing industry. The results highlight a visual approach towards establishing a common language between assembly and design teams to consider the requirements of an MAPL in product design.

Keywords: Design methodology, Mixed-product assembly system, Product architecture, Requirements

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1 INTRODUCTION

The shift towards mass customisation in recent decades has significantly increased the range of product varieties offered by manufacturing companies. Thus, gaining the capability to create greater product variety is highly critical for manufacturing systems as well as product design, and equally concerns both functions in manufacturing companies. Assembly systems are a significant part of manufacturing systems in relation to many aspects such as cost, time and creating product variety. Assembly is one of the most cost effective approaches to create high product variety (Hu *et al.* 2011). As a certain type of assembly systems which allows the creation of high product variety, Mixed-Product Assembly Lines (MPALs) are increasing in various industries and, as Lin and Chu (2013) indicated, have recently received significant attention from manufacturers. Based on the definitions applied in assembly sequencing problems, there are multiple products with only one variant in each production line for MPALs whereas there is only one product with multiple variants in each production line for a Mixed-Model Assembly Line (MMAL) (Lin and Chu 2013).

As variety increases, assembly operations can become more complex (Hu *et al.* 2008) and, due to the complexities of MPALs, the full potential of these assembly systems does not seem to be fully realised or investigated. The major challenges linked to MPALs, as reflected in the research, focus mainly on the balancing and sequencing problems for design and development of MPALs (see, e.g., (Vilarinho and Simaria 2002, Haq *et al.* 2006, Xu and Xiao 2009)). The majority of the research is based on suggesting mathematical algorithms for particular cases and is without a sharp focus on practical applications in industry. Despite significant academic efforts in assembly-line balancing and sequencing, mathematical algorithms were only used by a small percentage of companies during the 1970s and 1980s, and this gap has even widened recently (Boysen *et al.* 2007). In practice, the complexities of MPALs do not only revolve around the design and development of such assembly systems, but also concern product design for MPALs as an important aspect of establishing them. Manufacturing systems and in particular assembly systems represent significant investments in machine tools, material handling units and controllers; therefore, it is desirable to have product designs which best utilise the capabilities of manufacturing systems (ElMaraghy and Abbas 2015). Given that more than 70% of the final product costs are determined during design, assembly operation information and requirements are needed to determine product lifecycle management requirements and should be considered early in the design cycle using Concurrent Engineering (CE) (Yang *et al.* 2000, Demoly *et al.* 2012). Although various CE methodologies such as DFA techniques have been extensively discussed in recent decades, they do not directly address the recent challenges in aligning product design with the requirements of an MPAL. In the most commonly used DFA techniques, ease of assembly, cost and time of assembly are the focus (see, e.g., Boothroyd *et al.* (2011)). However, since most of the DFA techniques have been developed for a single product (Emmatty and Sarmah 2012), the requirements of assembly systems for creating product variety and the related complexities, as in an MPAL, are not considered in DFA techniques. In practice, in the absence of proper assembly-oriented product design approaches, increasing similarity among assembly operations for a range of different products from distinct product families and accordingly presenting MPAL’s requirements early for product design becomes a challenging task.

In product development, in order to manage complexity and to support product modularity, system or products are often broken down into manageable sub-systems or parts. Product architecture is one of the development decisions which most impacts a firm’s ability to efficiently deliver high product variety (Ulrich and Eppinger 2012). The approach of developing complex products or entire product families can be supported by using product architecture models in which high level descriptions improve multidisciplinary communication and cooperation (Bruun and Mortensen 2012). Because the product architecture constrains subsequent detail design decisions in this way, the team must consider the manufacturing implications of architecture (Ulrich and Eppinger 2012). In spite of various existing models for describing product architecture, similar approaches for describing the architecture of assembly systems and hence tackling MPAL’s complexity through breaking down assembly operations are absent. Considering this shortage and the emerging significance of MPALs for manufacturing companies, the objective of this paper is to suggest an assembly-oriented product design methodology which allows increasing similarities in assembly operations across distinct product families in an MPAL and enables the early presentation of MPAL's requirements for product design to designers. To fulfil the purpose of this paper, a product architecture modelling tool, the Interface Diagram (IFD) suggested by

Bruun *et al.* (2014), is utilised in the development of the methodology. The paper is based on a case study in a market-leading heavy vehicle manufacturing company which highlights the practical aspects of the proposed methodology for assembly and product design functions.

2 ANALYSING ASSEMBLY OPERATIONS BY UTILISING A PRODUCT ARCHITECTURE MODELLING TOOL

Product architecture, product modularity and commonality are among the different approaches of efficiently achieving product variety (ElMaraghy *et al.* 2013). Product architecture is the assignment of the functional elements of a product to the physical building blocks of the product (Ulrich and Eppinger 2012). Accordingly, the purpose of product architecture is to define the basic physical building blocks of the product in terms of their function and specify their interfaces to the rest of the device (Fixson 2007, Ulrich and Eppinger 2012). Architecture deals with three aspects; Decomposition: an architecture is a decomposition of a product into subsystems (modules); Arrangement: an architecture describes the relative arrangement of these sub-systems (modules); Interfaces: an architecture describes the relations (interfaces) between these sub-systems (modules) and with the surrounding environment (Bruun and Mortensen 2012). Developing product architecture has impacts on various aspects within a company. The effects through which product architecture characteristics, such as modularity and commonality can reduce costs are typically reduction of process complexity, increase of economies of scale, and risk pooling (Fixson 2007). According to Fixson (2007), these effects can vary across and within different activities such as design, manufacturing, inventory and use. Developing product architecture models also affects inter-organisational communication. The approach of developing complex products or entire product families can be supported by using product architecture models in which high-level descriptions improve multidisciplinary communication and cooperation (Bruun and Mortensen 2012). Various approaches are used to model product architecture. Some of these well-known approaches include Design Structure Matrix (DSM), Product Family Master Plan (PFMP), Bill of Material (BOM), Functional Structures, Decision Tree and Modular Functional Deployment (MFD). However, these approaches have some shortcomings in presenting product architecture. For instance, PFMP and BOM have no direct link to the manufacturing and supply chain, DSM cannot be used as a fully visual tool, and Decision Trees are considered more as product configuration methods rather than actual architecture descriptions. Bruun *et al.* (2014) introduced the Interface Diagram (IFD) as a graphical approach which represents different aspects of a product system and aims to support high-level decision-making related to system integration and modulirisation during the design process. IFD is a product architecture method, which describes product variety, models product families, identifies product platforms, supports modulirisation and architecture lifecycle. Moreover, IFD can be used as a product design tool for interface management, system integration, lifecycle considerations, visual modelling, communication, monitoring performance and as a basis for data model. Bruun *et al.* (2014) discussed that no single product architecture method or model addresses all phenomena handled in IFD. Additionally, the strength of IFD is that it can be used in companies developing diverse products and has been developed as a tool for practitioners (Bruun *et al.* 2014). Although the interfaces related to assembly are reflected in IFD, the method is recognised to provide less support when evaluating assembly variations. Assembly is the capstone process for product realisation, where component parts and subassemblies are integrated together to form the final products, and accordingly as product variety increases, assembly systems must be designed and operated to handle such high variety (Hu *et al.* 2011). In an MPAL where the diversity of assembly operations increases, there is a need to increase the similarity of assembly operations and quickly communicate the resulting requirements timely to product design teams through establishing a common language between assembly and design teams. A small number of studies exclusively focus on the modularity and commonality of processes (Fixson 2007). Additionally, despite the growing development in product related architecture research, studies focusing on architecture approaches in the context of assembly and manufacturing systems are scant. In the absence of proper methodologies for evaluating and increasing similarities between assembly operations of various distinct products, a product architecture modelling tool, such as IFD, can be utilised to analyse, evaluate, and present assembly operations for various products.

3 RESEARCH DESIGN AND CASE DESCRIPTION

3.1 Case-study design

A case study is the preferred scientific research method used to investigate and understand a specific phenomenon within its natural context (Eisenhardt 1989, Yin 2012). Given the objective of this paper, and to focus on the heavy vehicle manufacturing industry in which this area has been less explored, a single case study design is chosen as the research strategy. Areas where there is little understanding of how and why processes or phenomena occur, where the experiences of individuals and the contexts of actions are critical, or where theory and research are at their early, formative stages can be usefully addressed using case study research (Williamson 2002). Additionally, performing single case studies enables in-depth observations. For a given set of available resources, single case studies allow researchers to investigate phenomena in-depth in order to provide rich description and understanding (Williamson 2002, Karlsson 2010). Moreover, case study can result in practical implications, which is aligned with the objective of this research. Case study research can lead to new and creative insights, development of new theory and have high validity with practitioners: the ultimate users of research (Karlsson 2010). The case company is a market leader in the heavy vehicle manufacturing industry, which develops, manufactures and markets equipment for construction and related industries. Eight comprehensive and distinct product families are produced in sixteen manufacturing plants of the case company which are located in Asia, Europe and the Americas. The assembly lines in the case company are semi-automatic MMALs in which most of the operations are performed by assemblers. This paper investigates the Alpha project in the case company over an 8-month study period. The Alpha project aims at the standardisation of assembly operations and the reduction of variation in assembly operations performed on different products present in an MPAL. The primary motive in selecting the Alpha project as the case in this study has been its focus on creating common understanding about standardised assembly operations, and their consequences on product design, within a cross-functional team. The members of the cross-functional project team in the Alpha project held the following positions in the case company: manufacturing research manager, assembly manager, production engineer, technology platform and modular design support manager, product platform manager and product architecture global manager.

3.2 Data collection and analysis

The main sources of data collection in this case study were observations, interviews and project documents. Accordingly, the content of some of the meetings was recorded and transcribed for further analysis. Three authors of this paper have actively participated in the Alpha project in the case company. This position allowed the authors to take part in all of the meetings and workshops held in the case project and gave them full access to Alpha project documentation and team members. The documents used in this study cover various types of documents as presented in Table 1. Details regarding data collection and sources of evidence applied in the case study are presented in Table 1.

Data analysis was performed during and after the data collection as suggested by Merriam (2009). A generic approach to analyse collected qualitative data, suggested by Saunders *et al.* (2012) was followed for the analysis of the data in this study. First, categories which allow the comprehension of data were identified. Next, the data was attached from disparate sources to appropriate categories for integration. Thereafter, the categories were further developed to identify relationships and patterns.

Table 1. Data collection and sources of evidence.

Source	Techniques	No.	Participant(s)	Duration (minutes)
Observations	Project meetings Workshops Informal discussions	13 4 Daily	Cross-functional project team Cross-functional project team Cross-functional project team	30-150 240-300 8-Months
Interviews	In-depth interview	3 2	Alpha project manager Assembly Engineer	20-45 15-25
Documents	Project reports, presentations, E-mails, meeting notes, and company's procedures	---	---------	---------

Finally conclusions were drawn. To further increase the quality of the research results, the findings of the study were reported and discussed with the case company participants on several occasions.

4 EMPIRICAL FINDINGS

The heavy vehicle manufacturing industry is characterised by long assembly takt times, high assembly work content, wide variety in product design, and various product functions. Standardisation of assembly operations is expected to reduce variation in an MPAL in the case company. The reduction of balance losses, perceived complexity and quality risks allow the case company to expand its manufacturing footprint possibilities, global implementation of operational improvements and reduced investment costs through shared solutions.

Based on the general requirements of an MPAL to handle product variety, a common assembly sequence is proposed to be followed by all of the different product families in the MPAL. In addition, the use of common parts across various and distinct product families in the case company is regarded as a design characteristic. Therefore, the assembly function focuses on increasing the similarity of assembly operations among various product families or establishing similar assembly interfaces as a critical requirement of an MPAL for product design. It is essential that the requirements related to product design and raised by increased similarity in assembly operations are communicated early in the product realisation process and with familiar approaches to the designers. IFD, a product architecture visualisation tool which illustrates assembly interfaces, is selected for this purpose.

4.1 Product architecture framework and application of IFD

Efficient management of complexity and design structures, establishing a common language, and a common supporting tool in the organisation are the main drivers of architecture work. The elements which are described by Product Breakdown Structure are product of interest, systems, modules, interfaces and key components. A product consists of one or more modules and each module is composed of one or more key components. The term "module" refers to a grouping of physical elements connected by mechanical interfaces. Module drivers come from various stakeholders in the product life cycle: R&D, manufacturing, sourcing & suppliers, product management, logistics, sales & marketing, customers, service & aftermarket. Key components consist of a single or multiple parts at the lowest level of abstraction which the product of interest is managed on within architecture.

Managing interfaces is central to managing the complexity of a product and it enables the designer(s) to better understand and control the internal dependencies between various parts of a product. Interfaces are managed to fulfil the following purposes:

- to increase the standardisation of interfaces by re-using design solutions
- to increase the internal efficiency by decreasing the number of unique parts
- to reduce fabrication and assembly tooling investments by increasing the re-use of manufacturing operations and equipment
- to reduce design re-works due to unforeseen or uncommunicated interface changes

Different interfaces (e.g., mechanical, electrical, hydraulic, coolant, refrigerant, lubrication, fuel and fluids) are identified in the product architecture framework. However they are not equally important to keep stable over lifecycles, cross functions and cross products. Typically, mechanical interfaces, which describe the mechanical joining (e.g., nuts and bolts), are quite critical to understand as they characterise packaging and assembly perspectives. Nevertheless, no prioritisation of interfaces yet exists in the case company.

The lowest level of product architecture documentation in the product domain is reflected in the IFD. In IFD, a product is decomposed into manageable elements (interfaces, modules, system, and key components), enabling the design team to work efficiently on both the level of complete machines and individual part. The IFD visualises the Product Breakdown Structure and provides information about the type and responsibility for the interfaces, as well as information about quantity and responsibility of the modules. The advantages of utilising IFD for product design are identified as follows:

- IFD is a value adding structured process to encompass and validate a complex design task
- IFD reflects key design decisions and can support the design process by illustrating the status-quo, if updated
- IFD can be used as an effective means to engage and align the project team on the design task

Interfaces are described on different detail levels, as needed, in IFD. In the early phases of design, the interfaces only need to be identified at a high level. When the design is completed, interfaces are frozen, cannot be changed without control and are documented, for instance, in drawings. In product related functions and the IFD developed for product architecture, the similarity of the interfaces is not of interest. Additionally, positions and orientations of parts (as in the assembly operations) are not defined in the IFD, but are reflected in the CAD/Design structures. As a customer for interfaces, manufacturing needs pre-defined and common interfaces to allow common assembly methods and shared processes which call for a specific methodology in order to fulfil this purpose.

4.2 Assembly interfaces

Assembly interfaces describe how a product is assembled. An assembly interface is based on the three basic operations in assembly: picking the part, placing the part and attaching it. These three steps are performed differently, even for similar modules across distinct product families and even amongst various product variants within the same product family. In order to increase similarity between assembly operations and establish similar assembly interfaces, a common assembly sequence which is followed by all product families must first be established. To facilitate picking a module from distinct product families in an MPAL, common assembly sequence, common lifting interfaces and common lifting orientation must be secured in the product design. To facilitate the placing of a module, common positions on the module and common assembly directions/orientations need to be considered in the product design. To facilitate the attachment of a module in an MPAL, use of common fasteners, common tools, and common tool direction need to be fostered in the product design. An example of assembly interfaces illustrated on a powertrain module in is presented in Figure 1.

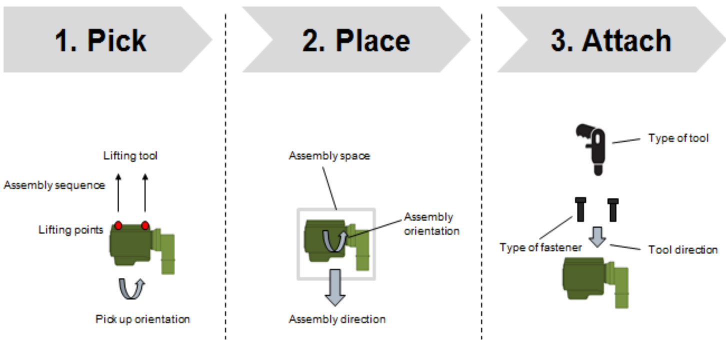

Figure 1. An example of an assembly interface described for a Powertrain module

4.3 Decomposition of product based on assembly operations

To establish a common language between product related functions and the assembly function, assembly interfaces can be defined by utilising the mechanical interfaces defined in the IFD. However, since the mechanical interfaces are defined on module level, according to product architecture framework, products must also be decomposed from an assembly operations standpoint in order to secure the interests of the assembly operations. Therefore, in a cross-functional approach, the product is decomposed into five different levels of granularity from an assembly operations standpoint: product, vehicle module, assembly unit, sub-assembly unit, and assembly elements (see Figure 2).

- The assembly element is the lowest level of assembly items and does not have a BOM
- Sub-assembly contains at least two assembly elements which are attached to each other, has a specified BOM and does not have a specified assembly sequence
- An assembly unit contains assembly elements and/or sub-assembly units, builds the vehicle module, can be attached to a vehicle module, and has a specified assembly sequence and BOM
- A vehicle module is the highest level of assembly items assembled on the main assembly line, contains assembly elements, sub-assembly units and assembly units with a specified sequence
- A product contains assembly elements, sub assembly units and vehicle modules

An assembly interface is defined between an assembled module and a receiving module(s) where the assembled module is the owner of the interface. Additionally, the assembly sequence must be defined for an assembly interface and the defining of the assembly module content. IFD is used to make reference to the assembly interfaces based on the definition of vehicle modules for assembly. Similar assembly interface means that the part is picked, placed and attached by assembler in the same way.

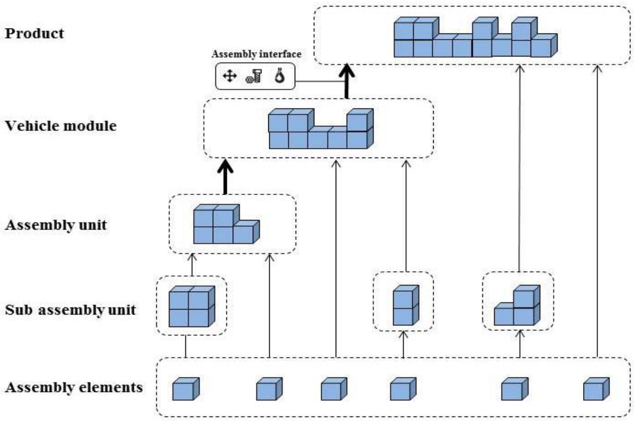

Figure 2. Decomposition of assembly elements

4.4 Using IFD in developing similar assembly interfaces for the Powertrain vehicle module

In the given example case, establishing similar assembly interfaces for the powertrain vehicle module in three different product variants (A, B, and C) from three distinct product families is investigated. The common assembly sequence for the three product families is defined on the level of vehicle modules and has 17 consecutive assembly steps. The common assembly sequence contains only those modules/assembly units which are common among the products which are considered to be assembled together on the MPAL. The initial four consecutive steps of the assembly sequence are Base, Axle, Hydraulic and Powertrain vehicle module assembly for each product (see Figure 3). As illustrated in Figure 3, the receiving modules and assembled modules according to the assembly sequence are identified. In the case of each product, the mechanical interfaces between every module with the other modules and their relevant interface IDs (as in the IFD) are illustrated. In the case of the Powertrain vehicle module for product A, three assembly interfaces exist in total: two interfaces with the Base module (IF-M. 224 and IF-M. 225) and one interface with the Axle module (IF-M.189). The first four assembly steps in the common assembly sequence, and per modules, are illustrated in Figure 3.

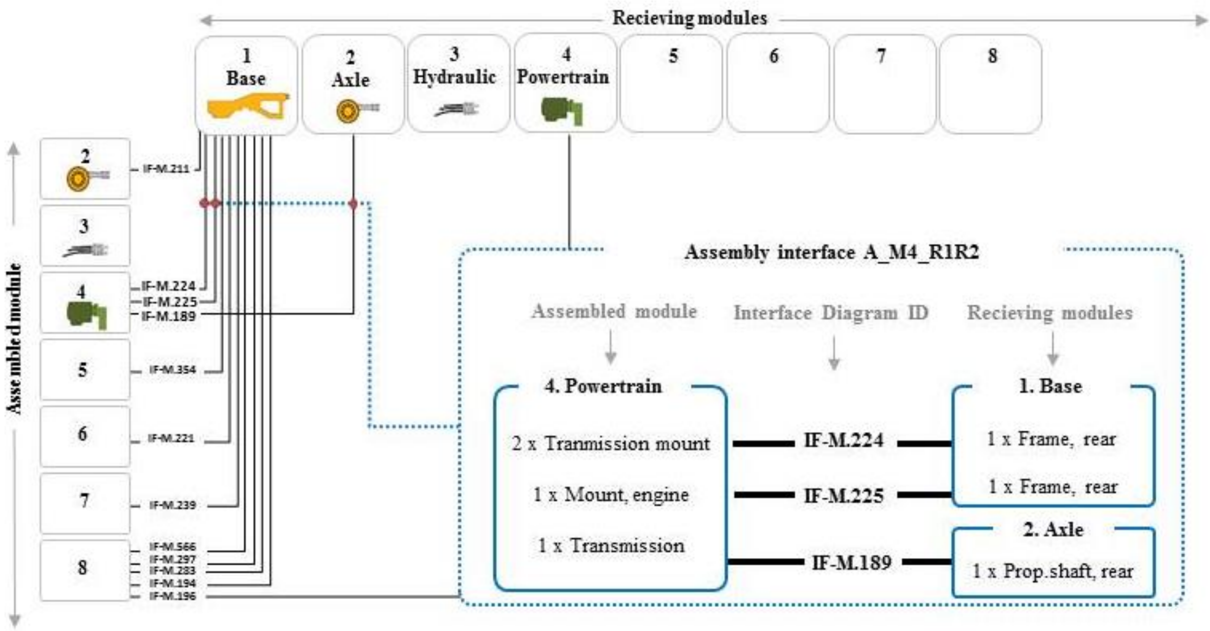

Figure 3. Illustration of Powertrain module assembly interfaces according to IFD and common assembly sequence.

To allow a comparison base for the assembly interfaces (pick, place and attach) of the Powertrain vehicle module across the three products, a set of symbols are defined. These symbols give general information regarding tool/equipment type, number of fasteners, dimension of fastener, type of attachment, total number of interfaces, position of interface, assembly direction, assembly connection, and tool direction used in each assembly interface (see Figure 4). Additionally, a set of evaluation criteria concerning ergonomics, safety, efficiency and complexity are defined.

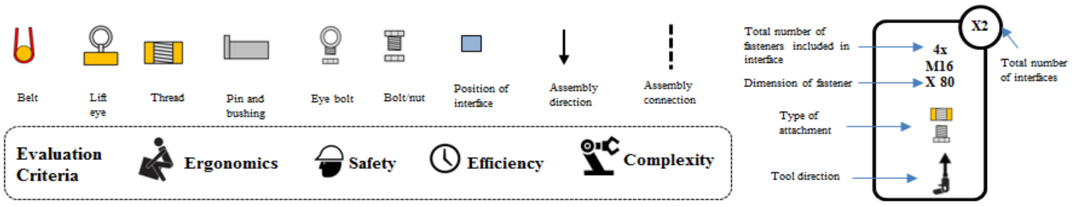

Figure 4. The symbols used in describing and evaluating assembly interfaces

As illustrated in Figure 5, the existing assembly interfaces (pick, place and attach) in the three products of A, B, and C are mapped and visualised. The required information for the mapping of each assembly interface is collected by a core assembly team through discussions with assembly experts, taking photos of assembly operations in different assembly plants with MMALs for each product. Fulfilment of each criterion is evaluated for each pick, place and attach operation in assembly interfaces and is marked as green (high), yellow (average), or red (low) by the product assembly experts. These criteria are used to allow comparisons of assembly interfaces across various products from distinct product families and with the aim of increasing the similarity of assembly interfaces.

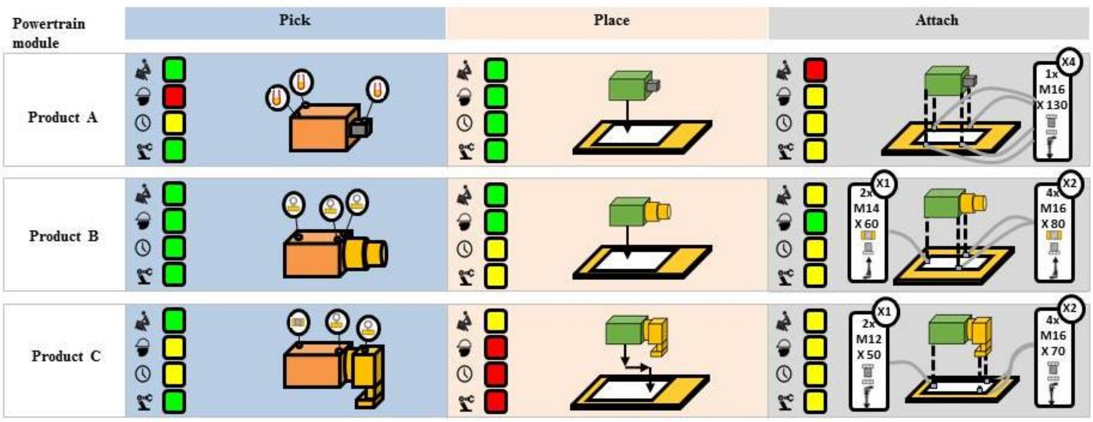

Figure 5. Mapping and comparison of assembly interfaces cross three product families

Following the comparison of various assembly interfaces for the Powertrain vehicle module in the three products of A, B, and C, and by considering the possibilities and constraints of assembly operations, a common wanted position for the Powertrain vehicle module design of the three products is developed (see Figure 6). The resulting wanted position is linked to each product module's interface ID and is also documented in a database to present and communicate the MPAL's assembly operation requirements for product design to product design team.

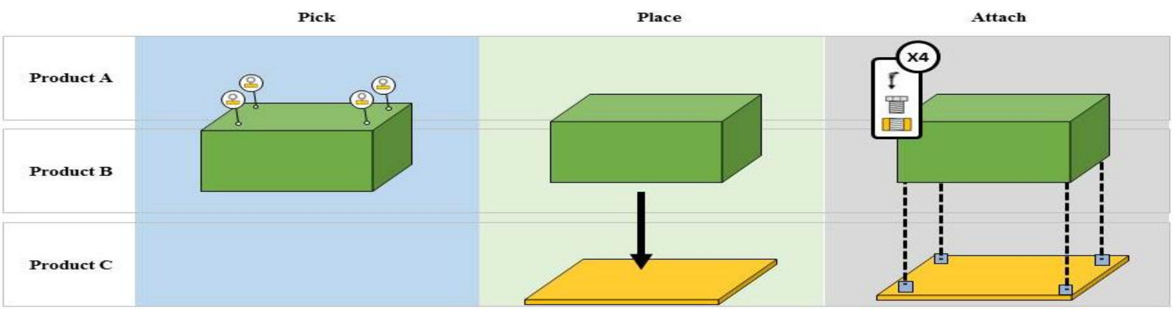

Figure 6. Proposed cross-product family assembly interface to the product design team

5 DISCUSSION AND CONCLUDING REMARKS

Growing significance of MPALs for manufacturing companies (Lin and Chu 2013), complexity of handling product variety in an MPAL (Hu *et al.* 2011), limited research on increasing the commonality of the processes (Fixson 2007) particularly for assembly operations cross-product families and its influence on product design in an MPAL, all highlight the need for a practical assembly-oriented product design methodology to tackle this challenge. The findings of the case study indicate a cross-functional approach led by assembly function to increase similarity among assembly operations in an MPAL and establish a common language to communicate these requirements from assembly to product design teams. For this purpose, the concept of assembly interface (pick, place, and attach) is used to break down the assembly operations into three basic and generic steps. The methodology for establishing similar assembly interfaces cross-product families is shown in
Figure 7.

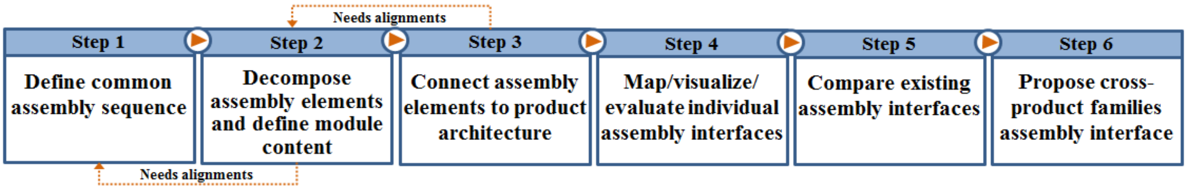

Figure 7. The six-step methodology to increase similarity of assembly operations in an MPAL

In order to support flexibility in an MPAL, the proposed methodology primarily aims to reduce the complexity of performing assembly operations on products from distinct product families for assemblers by securing similar assembly interfaces through product design. The proposed methodology for developing similar assembly interfaces is described at module level and has six main steps. Some of the steps (Step 1, 2, and 3) in the methodology are intertwined, as in practice their previous and following steps might need to be iterated to make the required alignments. Module content needs to be defined (Step 2) considering the common assembly sequence and thus, if needed, the common assembly sequence which is described based on modules (Step 1) must be adjusted accordingly. When connecting assembly elements to product architecture (Step 3), if variations between product modules as identified in product architecture and assembly modules (Step 2) exist, assembly modules must be aligned and the previous steps (Steps 1 and 2) might be repeated. As indicated in the findings, in the evaluation (Step 4) and comparison (Step 5) of assembly interfaces, quantitative approaches are not used and performing these steps is highly dependent on the expertise of the core assembly team, discussions and thorough documentation of the existing assembly interfaces. In all the steps of the proposed methodology, assembly function counts as the main and leading responsible function. However, in Steps 1, 2, 3 and 6, close collaboration between assembly function and product related functions, i.e. product architecture/product design teams, are required. Proposing assembly interface cross-product families (Step 6) can be realised by offering the best design solution or can be used as a starting point to generate new superior design solutions. Nevertheless, in the proposed methodology, which aims to establish a common language to communicate the requirements of an MPAL for product design between assembly and product functions, communication plays a significant role. To document, present and communicate similar assembly interfaces cross-product families, IFD (Bruun *et al.* 2014) as an exemplary visualisation tool for interfaces in product architecture was utilised in this study, use of which mainly concerns Steps 3 and 6 of the methodology. The suggested methodology addresses the three elements of architecture work: decomposition, arrangement, and interfaces, as discussed by Bruun and Mortensen (2012), particularly during the first three steps. IFD was used due to its applicability for practitioners in companies developing diverse products (Bruun *et al.* 2014) and its significance compared to other existing product architecture models. IFD provides an inclusive tool in addressing various product architecture aspects, graphically visualising the interfaces, improving multidisciplinary communication and cooperation, and handling the complexity of the development of various complex products (Bruun *et al.* 2014). However, this tool is also recognised to provide less support when evaluating assembly variations (Bruun *et al.* 2014). This issue is addressed through the suggested assembly-oriented product design methodology in this paper and can be included as an additional aspect for considering assembly operation similarity in the IFD tool.

The aim of this paper was to suggest an assembly-oriented product design methodology which allows increasing similarities in assembly operations across distinct product families in an MPAL and enables early documentation/presentation of MPAL's requirements for product design to designers, by using product architecture. The findings stem from a single case study in a market-leading heavy vehicle manufacturing company. Thus, the focus of the suggested methodology is on the semi-automatic MPAL in that particular industry; however, the results can also be generalised through providing insights for other industries with a wide range of complex physical products transitioning towards MPALs. Nevertheless, given the significance of modular approaches in the proposed methodology, which aims to support flexibility of an MPAL, investigating the link between modularity and flexibility is an interesting direction for future research.

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