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Convertibility evaluation of automated assembly system designs for high variety production

Malarvizhi Kaniappan Chinnathai*, Bugra Alkan, Robert Harrison

Automation Systems Group, WMG, University of Warwick, CV4 7AL, Coventry, West Midlands, UK

* Corresponding author. Tel.: +44 7831001684; *E-mail address:* M.Kaniappan-Chinnathai.1@warwick.ac.uk.

Abstract

The recent advancements in technology and the high volatility in automotive market compel industries to design their production systems to offer the required product variety. Although, paradigms such as reconfigurable modular designs, changeable manufacturing, holonic and agent based systems are widely discussed to satisfy the need for product variety management, it is essential to practically assess the initial design at a finer level of granularity, so that those designs deemed to lack necessary features can be flagged and optimised. In this research, convertibility expresses the ability of a system to change to accommodate product variety. The objective of this research is to evaluate the system design and quantify its responsiveness to change for product variety. To achieve this, automated assembly systems are decomposed into their constituent components followed by an evaluation of their contribution to the system's ability to change. In a similar manner, the system layout is analysed and the measures are expressed as a function of the layout and equipment convertibility. The results emphasize the issues with the considered layout configuration and system equipment. The proposed approach is demonstrated through the conceptual design of battery module assembly system, and the benefits of the model are elucidated.

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Keywords: Assembly systems; product variety; convertibility; design evaluation.

1. Introduction

Due to the increasing importance to satisfy customer needs, there has been a shift from mass production to mass customisation in the automotive market [1]. In order to survive in this competitive, turbulent and highly volatile market, enterprises have to employ new practices and strategies that can effectively accommodate high variety production to realise the advantage of mass customisation [2]. Thus, the concept of product variety management has gained significant importance within the last two decades. A key enabler for this is considered to be convertibility which is defined by [3] as "*the ability to easily transform the functionality of existing systems and machines to suit new production requirements*". To realise this, several approaches have been proposed for designing systems with the ability to handle the increasing product variety and fluctuating volume. However, unless an evaluation of the systems designed based on these approaches is performed, it is difficult to ascertain their capability to manage product variety. Hence, it is important to assess the system's responsiveness and ability to adapt to change, especially in the early design stages, since poor initial design increases the effort and time spent during redesign later in the design and engineering process[4]. Hence, this paper proposes a novel design support mechanism which can assess the concept designs of automated assembly systems, in an industrial-friendly way, for their readiness to change to a new configuration.

2. Literature review

Over the past few years, the domain of product variety management and flexible systems have received lot of attention. As a result, a number of models and methods to evaluate the flexibility of system have been researched in literature [5], [6]. However, there is limited research in the field of convertibility, which is considered as one of the characteristics of reconfigurability. Although convertibility is associated with product variety management, it is difficult to

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hypothesize a convertibility measurement using existing flexibility assessment models. Additionally, they need significant amount of data which is unavailable at the conceptual phase. Therefore, the literature study is limited to research on reconfigurability and convertibility evaluation.

Nomenclature

C_S	System convertibility
C_E	Equipment convertibility
C_C	Component convertibility
w_E	Weight for equipment convertibility
w_L	Weight for layout convertibility
C_L	Layout convertibility
$C_{SS,k}$	Convertibility of sub-system k (equipment level)
N	Number of sub-systems
M_k	Number of components in sub-system k
$f_{h,i}$	Hardware convertibility factor
$f_{s,j}$	Software convertibility factor
n	Number of hardware convertibility factors
m	Number of software convertibility factors
x	is 2 for controlled and 1 for uncontrolled components
N_k	Number of sub-systems, excluding sub-system k, shut down when sub-system k is under conversion
N_F	Total number of part flow connections, excluding input and output
N_{AWS}	Number of assembly workstations
N_R	Minimum number of replicated stations
L_A	Autonomy index
L_C	Connectivity index
L_R	Replication index

In the domain of reconfigurability, an approach for assessing the re-configurability of distributed manufacturing systems was proposed in [7]. In a similar study, Hasan et al. [8] investigated the re-configurability of machines through Multi-Attribute Utility Theory and Power function approximation. In the study, the re-configurability of machine configurations was evaluated based on machine attributes such as possible number of configurations, operational capability, effort required to reconfigure and production capacity of the machine. Farid [9] synthesised a re-configuration measure based on axiomatic design theory and design structure matrix to derive composite reconfiguration evaluation. A measure of the system's convertibility was formulated by the summation of the transportation and transformation convertibility in the work. Convertibility was measured in three different domains by [10], namely: configuration, machine, and material handling. The configuration convertibility was quantitatively evaluated with variables such as routing connections, replicated machines, and increment of change. Machine and material handling convertibility were intuitively scored. The combined score of the three domains provides a multi-dimensional convertibility value which is a representative of the system. This evaluation model was further improved by an adaptation to mixed-model assembly lines by [11], wherein a novel product family convertibility analysis was introduced.

An approach to measure the machine reconfigurability and operational capability was proposed by [12] and the possible number of possible machine configurations and the effort involved in changing them were identified. A metric called 'reconfiguration smoothness' was measured based on the cost, effort and time spent in system reconfiguration by [13]. Various aspects of change involved at machine level, system level and market level were considered. Each was expressed as a function of either the capabilities, or the machines added, removed or adjusted in the system. Ahmad et al. [14] describe an approach to evaluate the reconfigurability of an hydrogen fuel cell assembly system and analyse its suitability to the product. The approach intuitively measures a Reconfigurable Assembly System (RAS) for its conformity to the various aspects of reconfigurability including convertibility.

From the above-mentioned studies, it is observed that there is lack of sufficient research on the evaluation of convertibility of assembly systems in the concept phase that can assist in system redesign to achieve an optimum level of flexibility. To fulfil this gap, a novel evaluation model to assess the assembly system, for product variety at the concept stage, is proposed. The model can flag the system components at various levels of hierarchy that will later help formulate a multi-criteria redesign policy that can guide the designer to achieve a system capable of managing variety.

3. Methodology

The scope of this research is defined around the analysis of automated assembly system design convertibility based on its equipment structures and layout (Fig. 1). In this approach, an industrial assembly system is defined as a hierarchical network consisting of assembly workstations (AWS), connected through material handling units (MHU). System convertibility C_S is defined as an average of equipment convertibility C_E, and layout convertibility C_L and calculated by Eq. 1., where in order to provide decision-making flexibility in system assessment, w_E and w_L represent the weights for C_E and C_L respectively

$$C_S = w_E C_E + w_L C_L \tag{1}$$

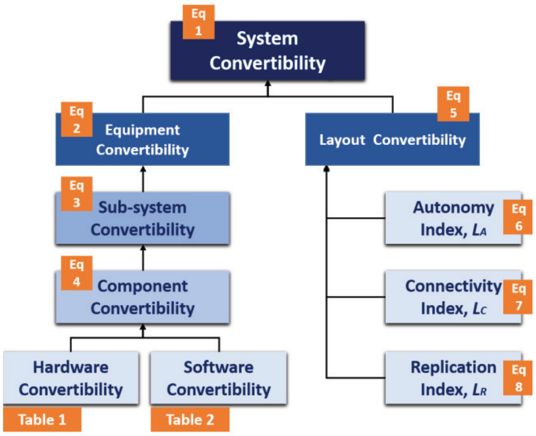


Fig. 1 The proposed methodology.

3.1. Equipment convertibility

Equipment convertibility C_E is the ability of equipment in a system to be changed or adjusted, by the addition, removal or adjustment of its constituent components. In this context, C_E is defined as a function of the convertibility of each assembly sub-system, N represents the number of sub-systems, C_{SS}, representing either workstations or material handling units, and is calculated as follows (Eq. 2).

$$C_E = \frac{\sum_{k=1}^{N} C_{SS,k}}{N} \tag{2}$$

In this study, a sub-system is assumed to be composed of a set of re-usable automation components (*e.g.* rotary table, clamp, gripper, *etc.*). M_k is defined as the number of components in sub-system k, C_{SS} is defined as the average component convertibility within the sub-system and it is calculated by Eq. 3.

$$C_{SS} = \frac{\sum_{l=1}^{M_k} C_{C,l}}{M_k} \tag{3}$$

A component is defined as the basic unit of a sub-system which at a finer level is composed of elements [15], and is capable of functioning either autonomously and/or integrated with other components to perform its desired function [16]. In this context, two types of classifications of component have been made; *i.e.* control and function. The classification based on control requirements categories components into two groups, *i.e.* controlled or non-controlled. Components that do not have control logic, and can be assessed only from the hardware perspective are denoted as non-controlled components (*e.g.* passive fixtures). On the other hand, controlled components can be actuated and hence are associated with control logic (e.g. active fixtures). Therefore, they must be assessed on both hardware and software domains. In function-based classification, the components are classified into five types *i.e.* motion, holding, joining, transport, and feeding components. By adapting the coding approach proposed in [17], the component convertibility, C_C, is calculated using the following equation, where ‘n’ and ‘m’ represent the number of hardware and software convertibility factors respectively.

$$C_C = \frac{1}{x}\left(\frac{\sum_i^n f_{h,i}^2}{n} + \frac{\sum_j^m f_{s,j}^2}{m}\right) \tag{4}$$

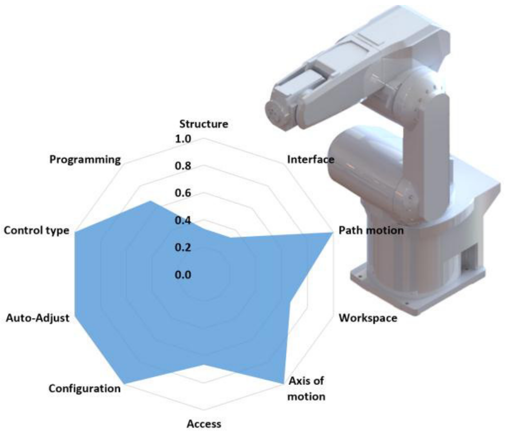
In this context, the hardware convertibility factors are calculated for all components regardless of their control behaviour, however the factors vary depending on their functions. Irrespective of the function of the component, the software convertibility factors are generic and calculated only for controlled components. Adapted from Table 1 and Table 2 represent hardware and software component convertibility factors respectively, and it is assumed in this study that these factors impact the system convertibility. However, components in an assembly system which are used for measurement or inspection, *e.g.* sensors, test gauge etc. and components which

Table 1. Hardware convertibility scores.

	Function	*i*	Criteria	0	0.333	0.667	1
1	Motion	1	Structure	-	Fixed	-	Modular
		2	Interface	Static/irremovable	Complex/non-standard	-	Simple/standard
		3	Path motion	Fixed	-	-	Variable
		4	Workspace	-	Tight	Appropriate	Large
		5	Axis of motion	-	1-2	3-4	5-6+
2	Holding	1	Structure	-	Fixed	Modular	Reconfigurable
		2	Interface	Static/irremovable	Complex/non-standard	-	Simple/standard
		3	DOF	-	0	1-2	3+
3	Transport	1	Structure	-	Fixed	-	Modular/extendable
		2	Interface	Static/irremovable	Complex/non-standard	-	Simple/standard
		3	Direction	-	Unidirectional	Bi-directional	Multi-directional
		4	Type	-	Synchronised	-	Asynchronised
		5	Routing	-	Fixed	-	Free
4	Joining	1	Structure	-	Fixed	Changeable - manual	Changeable – auto
		2	Interface	Static/irremovable	Complex/non-standard	-	Simple/standard
		3	Tool magazine	-	None/fixed	-	Changeable
5	Feeding	1	Structure	-	Fixed	-	Modular
		2	Interface	Static/irremovable	Complex/non-standard	-	Simple/standard
		3	Part orientation	None	Passive	-	Active

Table 2. Software convertibility scores.

i	Criteria	0	0.333	0.667	1
1	Openness	Closed	-	Limited	Open
2	Configuration	-	Fixed	-	Modular
3	Auto-adjustment	-	None	-	Available
4	Control type	-	Open-loop	-	Closed-loop
5	Programming	Online	Online – assistive	Offline – vendor specific	Offline – generic



$$C_C = \frac{1}{2}\left(\frac{0.333^2 + 0.333^2 + 1 + 0.667^2 + 1}{5} + \frac{0.667^2 + 1 + 1 + 1 + 0.667^2}{5}\right) = 0.656$$

Fig. 2 Convertibility analysis of 6 axis robot manipulator.

do not fall under any of the described categories are not considered in the model.

Figure 2 illustrates an example of convertibility for a 6 axis robot. The robot consists of elements such as actuators, sensors which are integrated to form the component. Unless the robot is modular, its elements, namely the actuators and sensors cannot be assessed at the hardware and software level. Therefore, the robot is considered as a standalone component and further decomposition is not beneficial for the considered model. It is assumed that the robot is mounted to a station and has a workspace appropriate for application. Since the robot is a motion component, the hardware convertibility factors for motion are considered. The robot structural configuration is fixed and has a non-standard interface with the station. It has variable motion path due to the vast workspace and ability to move to any point in that space. In this example, the robot software is limited in its openness as only certain parameters of the software can be modified. The robot movement is guided by a vision system that enables the robot to adjust according to changes in surroundings. This is captured by the criterion ‘auto-adjustment’. In cases of fixed automation which lack flexibility, the score will be 0.333 from the Table 2. The robot, inherently has closed-loop control because of the use of servo motors and the programming is done through offline vendor specific software. Accordingly, the component convertibility of the robot is calculated as 0.656.

3.2. Layout convertibility

Layout convertibility is defined as the ability to change the configuration and/or the part routing to accommodate new product variants. In this study, the system layout is represented as a network, with the nodes representing AWSs and the edges representing part flows. The layout convertibility is defined as the average of the indices describing various aspects of the system layout. Accordingly, it is calculated by Eq. 5.

$$C_L = \frac{L_A + L_C + L_R}{3} \tag{5}$$

3.2.1. Autonomy index, L_A

The layout autonomy index is used to express the system’s capability to be autonomous and not be affected or shutdown when conversion in a sub-system takes place. Accordingly, the layout autonomy is high if the system configuration is parallel since there is possibility of re-routing when a sub-system is shut down for conversion. L_A is calculated as Eq. 6.

$$L_A = 1 - \frac{\sum_{k=1}^{N} N_K}{N^2} \tag{6}$$

3.2.2. Connectivity index, L_C

According to [10], the degree of convertibility can be understood by evaluating the routing connections. This approach has been adapted in this research to assess the impact of the routing connections on the layout convertibility. The connectivity index is defined as a function of the existing number of material flow connections and the theoretical maximum and minimum number of flow connections (Eq. 7).

$$L_C = \frac{log_2(N_F - N_{AWS})}{log_2(((N_{AWS} + 2)(N_{AWS} + 1) - 2) - N_{AWS})} \tag{7}$$

It is important to note, since it is impractical to achieve theoretical maximum in real industrial scenarios, a logarithmic function is used to avoid unrealistic scoring for relatively low number of flow paths.

3.2.3. Replication index, L_R

Replication index is adapted from the study proposed by [10]. It is defined as the minimum number of AWSs that have the same operational capability, thereby enabling production of same product. It indicates the number of new product variants that can be introduced to the layout without stopping current production and it is calculated as (Eq. 8), where N_R represents the minimum number of replicated stations.

$$L_R = 1 - \frac{1}{N_R} \tag{8}$$

3.2.4. Illustrative example

An example of three types of layout configurations, each consisting of ten AWSs is depicted to explain the calculation of layout complexity (Fig. 3). Case A represents the stations are arranged in a parallel configuration with an index table transporting the product to all the stations. In case B, two gantries and three index tables are used for material handling. The layout configuration is hybrid with few stations in parallel and few in serial. Case C shows the stations arranged in a serial configuration with product being processed in each station before they can enter the next. Material transport between stations is with a modular conveyor system. Accordingly, the three cases are subjected to the layout convertibility indices and the results are shown in Table 3. It is assumed in this example, that all the part flow directions are unidirectional. From the table, the serial line has poor score for all three indices of layout convertibility. This is because all stations are dependent on one another, significantly reducing its convertibility. This indicates

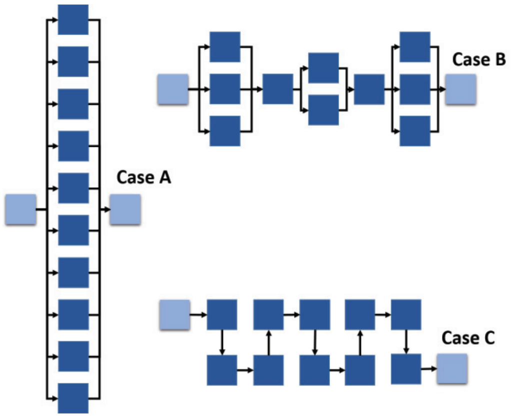


Fig. 3 Sample layout configurations of ten AWSs.

that when a station in serial line is shut down for reconfiguring it, the whole line shuts down.

In comparison, the hybrid configuration scores represent more convertibility than the serial configuration. This is due to the parallel stations that exist in the configuration. The parallel configuration has good scores for all three indices owing to the stations capability of behaving independent of the other stations during operation. Although this indicates the possibility of producing multiple variants in the same system, making it suitable for managing product variety, it is often impractical to be implemented due to the cost involved.

Table 3. Example layout convertibility calculations.

Case	L_A	L_C	L_R	C_L
A	1	0.481	0.9	0.794
B	0.82	0.374	0	0.398
C	0.1	0	0	0.033

4. Use case

The test case demonstrated comprises of nine AWSs and two MHUs, representing eleven subsystems in total for battery module assembly, as shown in Figure 4. Material handling sub-system 1 helps transportation of batteries, busbars, module covers and accessories from the warehouse to the assembly area and vice versa. Material handling sub-system 2 comprises of the modular conveyor unit, that transports the products between the stations. AWSs 1 and 2, perform the same operations of handling batteries and inserting them into the battery trays. AWSs 3 to 9 perform unique operations with each station having a defined operational capability. Stations 3, 4, and 5 locate the top battery tray, insert and tighten nuts, and join sub-modules respectively. Stations 6, 7 and 8 perform busbar locating, pulse arc welding and thermal pad assembly respectively. However, the need to perform busbar assembly and welding on the other side of the module, demands a reorientation operation. Therefore, the module is re-routed to station 5 where the module rotation is performed, after which it passes through the same sequence of assembly operations after which the module cover is assembled in station 9. The case study establishes the convertibility measurement for the conceptualized system and identifies aspects of system that should be considered for re-design. The component convertibility (Eq. 4) is calculated, according to the example shown in Fig 3, for each component present in a subsystem. From Fig. 4, ASW 1 is a subsystem consisting of 4 components and each of them have a convertibility score. This value is later input to Eq. 3 to obtain the convertibility score for each subsystem. Equation 2 is then utilized to find the overall equipment convertibility. In a similar manner, the layout convertibility assessment is performed using Eq. 5, 6 and 7 and can be visualized in Fig. 4. Finally, the system convertibility is evaluated using Eq. 1. It is important to bear in mind that the components should be classified as per section 3.1, and those components that are designed for a specific product, (e.g. work holders, pallet) are to be ignored.

4.1. *Results and discussions*

The results of the equipment and layout convertibility for the test case is shown in Fig. 4, from which the following can be inferred. MHU 2 and AWS 8 have low convertibility values and MHU1, AWSs 5, 7, and 9 have relatively high convertibility values. The low score of MHU2 is attributed to the conveyor and pallet locator, as can be seen from the component convertibility assessment. On the other hand, the high scores of MHU1 can be attributed to use of an AGV and a 6 axis robot in the system. The autonomy index value is calculated considering the possibility of interchanging AWS 1 and 2, and the connectivity index is calculated bearing in mind that the product can be routed to station 5 from station 8. The layout convertibility measure points out the inability for conveyor direction reversal and high level of station dependency. From Fig. 4, the equipment convertibility score is a bit higher than the layout convertibility score. This is due to the use of 6 axis robots in most of the sub-systems, however the absence of parallel stations and bi-directional product flow reduces the layout convertibility.

5. Conclusion and future work

In this paper, an approach based on heuristics is demonstrated with a battery module assembly test case and it is believed to have the following advantages *i*) ability to quickly assess designs that are detailed, as well as those that lack detail *ii*) reduced effort and cost involved to do the assessment *iii*) the practicality due to the component-based evaluation making it highly suitable for validating initial designs *iv*) quantification of a single design or comparison of multiple designs *v*) supporting optimisation of large assembly systems, where it is tedious to keep track of components used.

The research is an ongoing work, and the subjectivity of evaluating the different hardware and system will be reduced by optimizing the model and calibrating the scoring system for numerous test cases. Although currently, all components are assumed to be equal, empirical study will be done in the future to identify optimum weights for the different components. Additionally, the impact of convertibility at system level on the reconfiguration at the higher level of supervision control for scheduling, production execution etc. form part of future work.

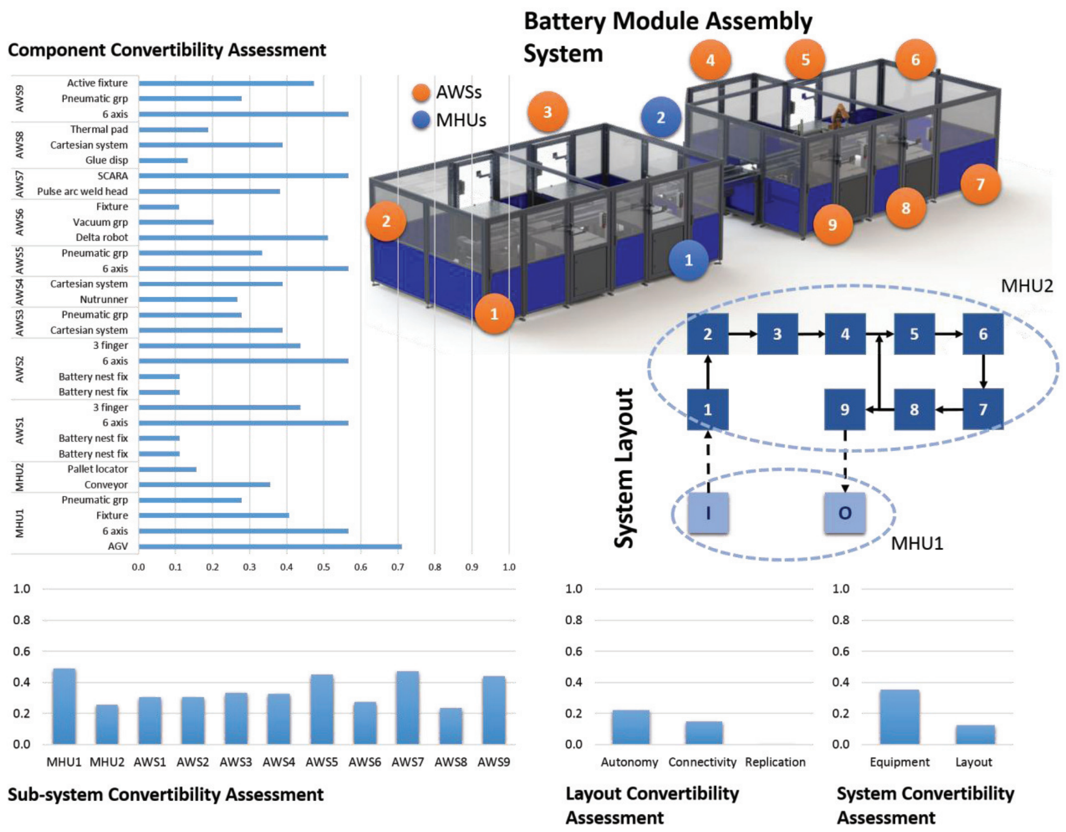


Fig. 4 Illustration of case study ($w_E = 0.5, w_L = 0.5$).

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