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Convertibility evaluation of automated assembly system designs for high variety production

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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

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

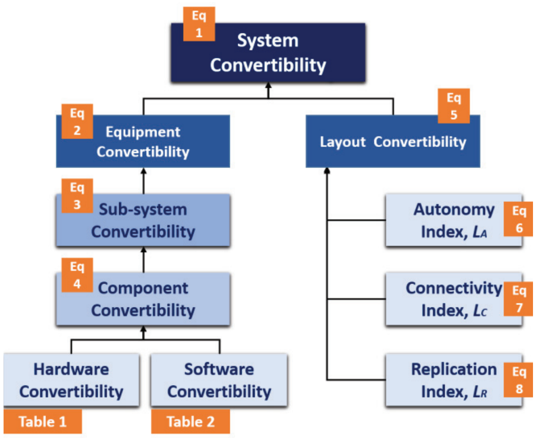

Fig. 1 The proposed methodology.