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Scalability and Convertibility Models and Approaches for Reconfigurable Manufacturing Environments

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Abstract. The reconfigurable manufacturing system (RMS) is one of the newest manufacturing paradigms. In this paradigm, machine components, machine software, or handling units can be inserted, removed, modified, or interchanged as needed and, where appropriate, imposed by the need to adapt and adjust quickly and cost-effectively to changing requirements. RMS is considered to be a convenient processing paradigm for the manufacture of varieties as well as a scalable enabler for this variety. Considered as two of the six main RMS characteristics, in this paper, we review the most used models and solving approaches dedicated to scalability and convertibility in reconfigurable manufacturing environments. Moreover, we highlight the most critical research gaps.

Keywords: Scalability, Convertibility, Reconfigurable Manufacturing Systems

1 Introduction

In today's world, the responsiveness of manufacturing systems and cost-efficiency are the main factors affecting companies' competitiveness. Especially in recent years, companies face the problem that customers prefer a greater variety of unpredictable quantities. In this case, the best way will be to design a modern manufacturing system with new features that will allow them to improve their capabilities in the future. RMS is the cornerstone of this manufacturing model. The idea of (RMS) became well known at the end of the 20th century, introduced by [1] as a potential solution to the problems mentioned above, which can be applied to meet the needs of customers and the environment of demand for functions and production capacity. Thanks to its flexible structure and six key characteristics: modularity, integrability, customization, convertibility, scalability, and diagnosability [2].

In this research work, we focus on two major RMS characteristics, namely scalability and convertibility. We present the existing models and approaches. More precisely, Section 2 presents some research works dedicated to the six RMS characteristics. Section 3 analyses some models and approaches used to address scalability problems. Section 4 discusses some models of convertibility and their solving approaches. Section 5 highlights the most important research gaps in the field. Finally, Section 6 concludes the paper.

2 RMS Characteristics

Due to its six key characteristics, namely integrability, modularity, customization, convertibility, scalability, and diagnosability [2], RMS is considered one of the most appropriate paradigms to address today's industrial problems. Moreover, even if scalability has attacked researchers' intentions, convertibility is still an open question. In the following, we provide some recent definitions of the six characteristics [3].

- **Scalability (design for capacity changes):** The capability of modifying production capacity by adding or removing resources and/or changing system components.
- **Convertibility (design for functionality changes):** The capability of transforming the functionality of existing systems and machines to fit new production requirements.
- **Diagnosability (design for easy diagnostics):** The capability of real-time monitoring the product quality and rapidly diagnosing the root causes of product defects.
- **Customization (flexibility limited to part family):** System or machine flexibility around a part family, obtaining thereby customized flexibility within the part family
- **Modularity (modular components):** The compartmentalization of operational functions into units that can be manipulated between alternative production schemes
- **Integrability (interfaces for rapid integration):** The capability of integrating modules rapidly and precisely by hardware and software interfaces.

3 Scalability Models and Approaches

The scalable architecture enables the company to have a manufacturing infrastructure that meets current demand and improves production to respond quickly to customer demand. A review of the literature on the scalability of manufacturing systems shows that there are two main lines of research in this area [4]:

- Design of RMS focused on increasing their scalability level.
- Capacity planning using the scalability of RMS to adapt their production throughput to the existing demand.

Model 1: [5] considered RMS scalability based on the transfer line (TL) type structure with batch production for mass production. They modeled conventional transfer line systems and the homogeneous paralleling flow line (HPFL) system. Finally, they concluded that *the characteristic of cost-effective capacity changes in HPFL meets the scalability requirements of reconfigurable manufacturing systems.*

1. Conventional Transfer Line System

The system density function $P(\tau)$ is given by:

$$P(\tau) = \sum_{i=1}^q p_i(\tau) = \sum_{i=1}^q \frac{n_i}{n_s} \delta(\tau - \tau_i) \quad (1)$$

where $\tau_i (i \in 1, 2, \dots, q)$ is the cycle time, δ is Dirac delta function, q is the number of distinct cycle time, n_i is the stage frequency for cycle time and $n_s = \sum_{i=1}^q n_i$, $p_i(\tau)$ is the stage density function.

2. Homogeneous Paralleling Flow Line (HPFL) System

The minimum required number of stations for stages with cycle time τ can be defined as:

$$g(\tau, v) = \left\lceil \frac{v}{T_a} \tau \right\rceil \quad (2)$$

From equations (1) and (2), the minimum number of required stations is given by:

$$n(\tau, v) = n_s P(\tau) g(\tau, v) = \sum_{i=1}^q n_i \delta(\tau - \tau_i) \left\lceil \frac{v}{T_a} \tau \right\rceil \quad (3)$$

Here, the minimum number of required stations $N(v)$ for the entire system with demand “ v ” is given by:

$$N(v) = \int_0^{\infty} n(\tau, v) d\tau = \int_0^{\infty} \sum_{i=1}^q n_i \delta(\tau - \tau_i) \left\lceil \frac{v}{T_a} \tau \right\rceil d\tau = \sum_{i=1}^q n_i \left\lceil \frac{v}{T_a} \tau_i \right\rceil \quad (4)$$

where T_a : is the available working time of the system. If the cost of stations is identical and equal to c , then the total station cost of the system is given by:

$$C(v) = c \times N(v) \quad (5)$$

Model 2: In [6], the dynamic scalability process in RMS is modeled, where different capacity scalability policies are evaluated for different demand scenarios. The model represents capacity scalability as a scaling rate $SR(t)$ determined by the required capacity $RC(t)$ together with the scalability delay SDT given by:

$$SR(t) = \frac{C(t) - RC(t)}{SDT} \quad (6)$$

where $C(t)$ is the capacity level at time t . Moreover, the inventory adjustment rate at time t , $AI(t)$ is controlled by the inventory gap between the desired inventory level $DI(t)$ and current inventory level $I(t)$ given by:

$$AI(t) = \frac{DI(t) - I(t)}{IAT} \quad (7)$$

where IAT is the inventory adjustment time (i.e., the time required to react for inventory discrepancy between the current inventory level and the desired level).

Furthermore, the production rate $PR(t)$ is controlled by the capacity scalability level given by:

$$PR(t) = \frac{C(t) * U}{MUT} \quad (8)$$

where U is the utilization level of the available capacity, and MUT is the manufacturing unit time (i.e., used to switch from stock to rate to maintain dimensional balance). The customer orders fulfillment at time t , $OFR(t)$ is controlled by the shipment rate $ShR(t)$ and given by:

$$OFR(t) = ShR(t) = \text{Min}(DSR(t), MSR(t)) \quad (9)$$

where $MSR(t)$ is the maximum shipment rate at time t (i.e., depends on the system's current inventory) and $DSR(t)$ is the desired shipment rate at time t .

Model 3: Due to the capacity scalability, [7] developed a dynamic model for the reconfigurable manufacturing systems whereby various system configurations, based on control theory and feedback analysis, can be implemented in response to changing demand. The proposed model contains two feedback loops. The first loop concerns the *WIP* error, where the second loop addresses the production rate error. They established a transfer function (Eq. 10) for the system based on the schema bloc depicted in Fig. 1.

$$\frac{PR}{Cap^*} = \frac{G_W(T_D^{-1} + S) + G_C T_{LT}^{-1} T_D^{-1}}{S^2 + S(T_D^{-1} + T_{LT}^{-1} + G_W) + (G_W T_{LT} + G_C + 1) T_{LT}^{-1} T_D^{-1}} \quad (10)$$

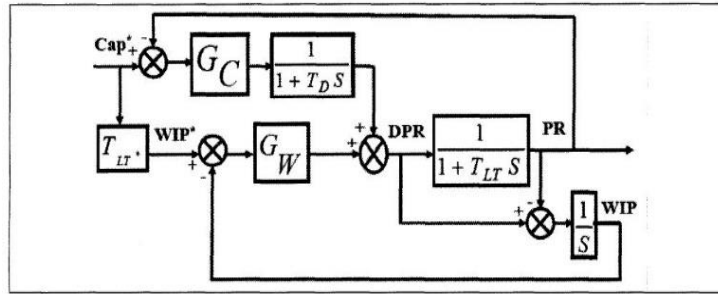


Fig. 1. Block Diagram for Dynamic RMS Model [7]

Finally, to illustrate the proposed dynamic approach, a simple numerical example of a reconfigurable machine shop with 40K goods per day is simulated, applying different controllers P, PD, PI, and PID. Where: *WIP**: Desired work in process level (parts), *WIP*: Actual *WIP* level (parts), *DPR*: Desired production rate (parts/days), *PR*: Actual production rate (parts/days), *TLT**: Expected lead time (days), *TLT*: Lead time (days), *GW*: *WIP* control gain (1/day), *Cap**: Desired capacity rate (parts/days), *GC*: Capacity scalability control gain (parts/days) and *TD*: Capacity installation delay time (days).

Model 4: To understand the relationship between management level and operational level in capacity scalability problem in RMS, [8] used the Shema bloc of Fig. 2 to establish transfer function for the system (Eq. 11), where the dynamic approach for capacity scalability and the classical static approach are compared.

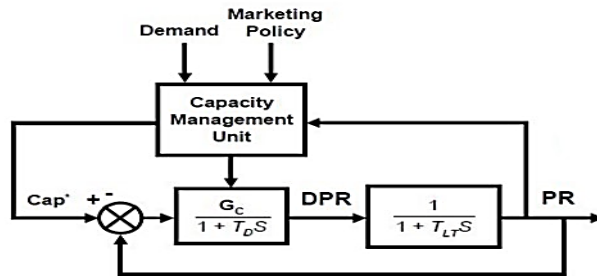


Fig. 2. Capacity Scalability System Block Diagram [8]

The problem is solved using the multi-objective weighted sum method.

$$\frac{PR}{Cap^*} = \frac{G_C T_{LT}^{-1} T_D^{-1}}{S^2 + S(T_{LT}^{-1} + T_D^{-1}) + (1 + G_C) T_{LT}^{-1} T_D^{-1}} \quad (11)$$

Model 5: [9] proposed a practical method to determine the most cost-effective system reconfiguration to meet new market demand. An optimization model is proposed for scalability planning, where a case study is illustrated to examine and validate the approach. They defined scalability Sc as:

$$Sc = 100 - \text{smallest incremental capacity in percentage}$$

As input for the model, they used: configuration information, stage characteristics, manufacturing machine reliability information, and demand, where scalability planning aims to minimize the number of machines needed (Eq. 12). A genetic algorithm-based approach is used to solve the problem.

$$\text{Min} \left(\sum_{i=1}^L (N_i + M[i]) \right) \quad (12)$$

Model 6: [10] used the mathematical model of [11] that encompasses the product complexity in the system scalability with a variable number of stages. A case study is presented to show the capabilities of the proposed model. Based on the scalability of the available system, the following issues have been discussed:

- Machines added per stage should be minimized (Eq. 13).
- Stages added (if required) for the new part be minimized (Eq. 14).
- Maximization of throughput (Eq. 15).

$$\min \sum_{l=1}^L \Delta_l + \frac{TH_{new}}{TH(M, T, t)} \quad (13)$$

$$\min \sum_{i=1}^I \sum_{l=1}^L S_{ij}(\Delta_l) \quad (14)$$

$$\max TH(M, T, t) \quad (15)$$

where S : existing machine stage, M : existing machines per stage, C : existing machine capabilities, and TH : throughput. They tested several scenarios of individual parts segregated into two main groups. The first group contributes towards the part manufacturing complexity, and the second group contributes mainly towards the product assembly complexity.

Model 8: [12] represented the dynamic capacity evolution by:

$$y_k = \min(C_k, D_k) \quad (16)$$

$$C_{k+1} = C_k + X_{k-T} \quad (17)$$

where C_k represents the firm's capacity level at time k , X is the control input that defines the addition or removal of capacity, and y_k represents the firm's sales. The delay

time T is limited to be a multiple of the time increment K . The capacity management cost is given by:

$$G_k(C_k) = E\{(\gamma_P - P)\min(C_k, D_k) + \gamma_S \max(0, D_k - C_k) + \gamma_H C_k\} \quad (18)$$

where γ_P : is the service costs per unit to produce, P : is the sold fixed price per unit, γ_S : is the penalty cost per unit, γ_H is the holding or overhead cost, per unit of capacity at each period, γ_N is the remaining capacity (i.e., can be sold for a salvage value per unit of terminal capacity), β is the discount factor and $M_k(X_k)$ is the cost of expanding/subtracting capacity incurred at time k . Hence, to minimize the expected discounted cost, Eq. 19 is used.

$$\min_{X_0 \dots X_{N-1}} \left\{ -\beta^N \gamma_N C_N + \sum_{k=0}^{N-1} \beta^k [G_k(C_{k+1}) + M_k(X_k)] \right\} \quad (19)$$

In the end, they applied a feedback control system approach to the capacity management problem for sub-optimal solutions.

4 Convertibility Models and Approaches

In this section, we focus mainly on convertibility. It is defined in [3] as “*the capability to transform the functionality of existing systems and machines to fit new production requirements.*”

Model 1: The first mathematical model used to measure and quantify systems convertibility C_S was proposed in [13]. The model combines three metrics, including configuration convertibility C_C , machine convertibility C_M , and material handling convertibility C_H , given by:

$$C_S = w_1 C_C + w_2 C_M + w_3 C_H \quad (20)$$

where w_1 , w_2 and w_3 are the associated weights.

The metrics are evaluated using Eqs. 21, 22, 23, and 24.

$$C_C = \frac{R * X}{I} \quad (21)$$

where R : refers to the number of routing connections in each configuration, X : is the minimum number of replicated machines in the process plan at a particular stage, and I : is the minimum increment of conversion. Normalization of Eq. 21 is proposed:

$$C_{C\text{-normalized}} = 1 + \left[\frac{\log\left(\frac{C_C'}{C_C' \text{ serial}}\right)}{\log\left(\frac{C_C' \text{ parallel}}{C_C' \text{ serial}}\right) \times \frac{1}{9}} \right] \quad (22)$$

$$C_M = \frac{\sum_{i=1}^N C_M'}{N} \quad (23)$$

$$C_H = \frac{\sum_{i=1}^N C_H'}{N} \quad (24)$$

Furthermore, [14] developed an index to measure RMS's reconfigurability using multi-attribute utility theory, where convertibility is considered using model 1 above. In [15], a NSGA II based-approach for machine selection is proposed based on three criteria, namely machine utilization, configuration convertibility, modeled using Eqs.21 and 22, along with machines costs. Moreover, [16] measured the reconfigurability of manufacturing systems by quantifying RMS characteristics, where Eqs.21 and 22 are employed to measure the convertibility (C_c).

According to [17], if more information is available about the number of processed variants (product family), model 1 needs an adaptation. To evaluate the configuration convertibility of a mixed model assembly line, a fourth parameter is introduced to cope with the system's variation and given by:

$$Y = \frac{\text{Variants number}}{\text{Workstations number}} \quad (25)$$

The new configuration convertibility C_{CY} is given by:

$$C_{CY} = C_{c, \text{Normalized}} * Y \quad (26)$$

Besides, they proposed a model to quantify product convertibility C_{PF} given by:

$$C_{PF} = a * b \quad (27)$$

$$a = \frac{\text{Total number of components with setting interfaces}}{\text{Total number of setting interfaces}} \quad (28)$$

$$b = \frac{\text{Total number of components with gripping interfaces}}{\text{Total number of gripping interfaces}}$$

Finally, the product convertibility C_{PF} can be computed as:

$$C_{PF} = \frac{\sum_{k=1}^l C_{F_k}}{\sum_{k=1}^l I_{sF_k}} * \frac{\sum_{j=1}^m C_{F_j}}{\sum_{j=1}^m I_{gF_j}} \quad (29)$$

where F_i is the i th component family, l is the number of component families with setting interfaces, m is the number of component families with gripping interfaces, C_F is the number of components in F_i and I_{gF} is the number of gripping interfaces in F_i .

They used an example of an automobile industry plant to measure each product family's convertibility and justify selecting the plant that can easily manufacture variant x . Finally, the convertibility indicator equation is:

$$C_S = w_1 C_{CY} + w_2 C_{WS} + w_3 C_H + w_4 C_{PF} \quad (30)$$

Model 2: [18] provided an analysis of automated assembly system design convertibility based on its equipment structures and layout, where system convertibility C_S is defined as a “sum of equipment convertibility C_E , and layout convertibility C_L ” and calculated using Eq. 31:

$$C_S = w_E C_E + w_L C_L \quad (31)$$

- The equipment convertibility (C_E):

$$C_E = \frac{\sum_{k=1}^N C_{SS,k}}{N} \quad (32)$$

where $C_{SS,k}$ convertibility of sub-system k (equipment level), N is the number of sub-systems and k sub-system.

- Layout convertibility (C_L):

$$C_L = \frac{L_A + L_C + L_R}{3} \quad (33)$$

where: L_A is the autonomy index, L_C is the connectivity index, and L_R is the replication index. Finally, they presented a test case based on heuristics for battery module assembly to evaluate their approach.

5 Discussions

RMS is a highly active research field with several state-of-the-art contributions in various disciplines, including design, layout optimization, reconfigurable control, process planning/process generation, and production scheduling. From the above literature review, we can claim the following gaps:

1. Only linear models were considered for the dynamic cases to model scalability, ignoring non-linearity, which is more representative of reality. In contrast, no dynamic model has been shown in the literature for convertibility
2. Scalability has gained researchers' intention where several models are presented, while for convertibility, all the presented models are based on a single extended model.
3. Simulation-based optimization may be used to enable the application of alternative optimization methods. Furthermore, various simulation approaches such as discrete-event simulation can be utilized to mimic scalability, as well as other robust control mechanisms.
4. The system expansion and the addition of machines will increase waste and energy consumption, which were not considered in any model.
5. The number of employees and work shifts were not included, nor was the control system's adjustment, which raises the frequency of alerts. This lack of information and control will affect the product's quality and ultimately lead to yield loss.

6 Conclusion

Manufacturing firms must adjust their manufacturing methods to adapt to changing market demands. RMS is one method for accomplishing this goal by promoting its flexibility while optimizing efficiency and costs.

This research work tackled two main RMS characteristics that improve the system's overall performance: convertibility and scalability. Some models and approaches were

presented and analyzed. Nevertheless, we found out that several models exist in the literature for scalability where only one model was proposed and extended to deal with convertibility. Moreover, there is a dearth of research works that integrate sustainability while modeling the characteristics.

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