International Journal of Production Research
Vol. 49, No. 5, 1 March 2011, 1319–1335

Performance evaluation of reconfigurable manufacturing systems via holonic architecture and the analytic network process

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(*Final version received August 2010*)

The paper develops holonic architecture for reconfigurable manufacturing systems (RMS), which are capable of adapting to unpredictable changes in demands. RMS are designed to produce various products grouped into families in a short time at low cost. A holonic structure reflecting basic holons for RMS is developed and then linked to an analytical network process (ANP) model, as a multi-criteria approach, to evaluate system performance. The proposed generic model provides flexibility for holons and facilitates evaluation of RMS considering economical and operational aspects as the main performance objectives. Moreover, new requirements such as functionality and capacity for process reconfigurability along with reconfiguration time/cost are taken into account. By allowing interactions among all the ANP clusters and their relevant elements in terms of outer and inner dependencies, the critical factors affecting the system performance are explored and evaluated through a case study. In particular, the criticality of the elements affecting the system performance will be assessed with respect to planning horizons, economical/operational aspects, and process reconfigurability based on available capacity and feasible functionality.

Keywords: holonic manufacturing; reconfigurable manufacturing systems (RMS); analytical network process (ANP)

1. Introduction

Market demand fluctuations and upcoming social, economical and environmental pressures need effective manufacturing systems (MS) to adapt themselves to various situations. Global interdependencies between manufacturing companies and market dynamics create new requirements to be challenged. Therefore, several manufacturing paradigms such as agile manufacturing system (AMS), holonic manufacturing systems (HMS), and reconfigurable manufacturing systems (RMS) are developed as alternative solutions for advanced MS. These paradigms have a common objective of manufacturing of product variants in a short time at low cost in a dynamic and adaptive environment.

AMS is designed based on processing and delivery time of products, and mainly offers a strategic perspective and production policy of a MS (DeVor *et al.* 1997, Hawker and Waskiewicz 1997). In contrast, HMS is mainly designed to minimise production and inventory cost of components in running manufacturing process, and usually offers an operational perspective based on simulation (Covanich and McFarlane 2009), mainly for

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ISSN 0020–7543 print/ISSN 1366–588X online

DOI: 10.1080/00207543.2010.520989
http://www.informaworld.com

scheduling policy of a MS (Giret and Botti 2009, Pujo *et al*. 2009). Whereas, RMS could contribute to both levels of system level (strategic/tactical aspect) and machine level (operational aspect) of a MS (Mehrabi *et al*. 2000, Bruccoleria *et al*. 2006) based upon product family formations (Galan *et al*. 2007) and a reconfiguration link between market and manufacturing processes (Abdi and Labib 2004).

In spite of these distinctions, holonic architecture can play a part in reconfiguring the control system of an established RMS in different post-design levels such as planning, scheduling and execution. Most research work on HMS has focused on the selection of manufacturing control architecture, e.g. Covanich and McFarlane (2009), or the allocation of control functionality to software and control objects corresponding to physical machines and products, e.g. Van Brussei *et al*. (1998). However, very few of them such as Covanich and McFarlane (2009) and Fardid (2007) considered reconfigurability in performance measurement. This paper is intended to explore critical factors, mainly related to reconfigurability via holonic architecture without benchmarking and/or selection of MS architecture/system choices.

This paper is intended to structure a combination of strategic objectives with tactical/operational elements influencing RMS performance through proposing an analytical approach. The paper is structured as follows. Firstly, the process of RMS performance evaluation is highlighted. Secondly, a review of literature on analytical hierarchy process (AHP), analytical network process (ANP), and holonic architecture, along with concepts of potential linked applications in RMS, are presented. Accordingly, we describe how the set of holons used in the architecture can be transformed into elements required for developing an AHP/ANP structure. Finally, critical analysis of RMS performance is performed via the proposed ANP model through using SuperDecison software (SuperDecison 2009) in a case study.

2. RMS performance evaluation

RMS is designed at the outset for rapid changes in hardware and software components in order to quickly adjust to production capacity and functionality within a part family in response to sudden changes in the market or in regulatory requirements (Koren *et al*. 1999). Therefore, RMS must be open-ended systems which could be described by key characteristics of modularity, integer-ability, convertibility, diagnosability, and customisation (Mehrabi *et al*. 2000), and particularly changeable functionality and scalable capacity (Koren 2005). Further research on RMS changeability must concentrate on development of functional models to obtain a generic structure and methods which are adaptable and scaleable (Wiendahl *et al*. 2007).

In most conventional models developed for evaluating MS performance, importance of reconfiguration time, reconfiguration cost and product variants have been ignored or insufficiently distinguished. In addition, an unfitting approach of performance evaluation along with increasing uncertainties caused by external factors, e.g. global economic slowdown and/internal factors, e.g. technology changes might lead to an incorrect judgment on performance of a running MS.

One of the important issues in a manufacturing process design is to evaluate the feasibility of system configurations for different product types. Therefore, a systematic method to evaluate the quality and productivity of systems with different configurations is necessary (Yang and Hu 2000).

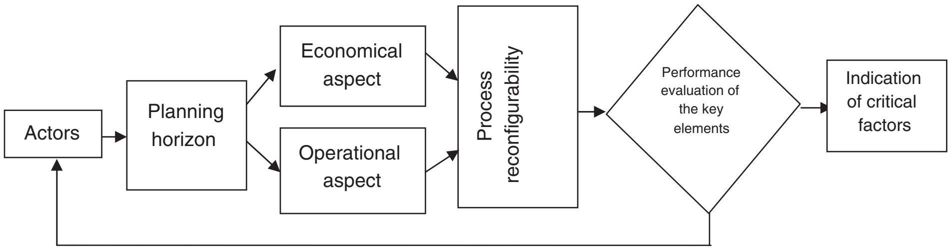


Figure 1. RMS performance evaluation process with the building blocks.

Application of performance measurement via control-theoretic approaches in manufacturing systems have been excessively researched on the operational and machine levels but not as much on the system and enterprise levels (Deif and ElMaraghy 2007). System based evaluation approaches are important for RMS as such systems need to be dynamic and controllable in order to achieve target objectives in terms of profit and process reconfigurability.

Reconfiguration processes can be split into two phases of reconfiguration potential (concerned with feasible system configurations), and ease of reconfiguration (concerned with efforts required for reconfiguration considering limited available resources of time, cost and skill) (Farid 2008, Covanich and McFarlane 2009). Therefore, both economic and operational aspects need to be considered in order to make a decision in support of resource reconfiguration policies. Furthermore, top management and experienced engineers involved with design and running RMS processes must participate in modelling and evaluation process to jointly investigate the crucial factors affecting the system through a multi-criteria evaluation approach.

Figure 1 depicts the process of performance evaluation with the RMS major drivers. Common performance factors for conventional MS such as economical and operational aspects are considered in the process. In addition, new requirements of functionality and capacity for process reconfigurability along with reconfiguration time/cost are taken into account. By allowing interactions and evaluation among all building blocks and their corresponding elements, critical factors affecting system performance can be explored.

3. The AHP/ANP

Saaty (1980, 1996) developed the AHP and the ANP in order to analyse multiple criteria decision making (MCDM) problems. AHP is a method that helps decision-makers facing a complex problem with multiple conflicting and subjective criteria; for example, location or investment selection, projects ranking and so forth (Ishizaka and Labib 2009). AHP models a hierarchical decision problem framework but it is limited to those problems that have a hierarchical structure or unidirectional relationships.

AHP could help to find an alternative decision, which will be the most appropriate feasible choice with best rating via synthesising all elements preferences. The MCDM problem is transformed into a hierarchy of sub-problems, which could be independently evaluated and analysed. Sub-problem criteria might have heterogeneous characteristics as they could be specifically/vaguely defined along with crisp/fuzzy values. Relative preferences of elements with respect to higher-level elements are quantified by the decisive actors. Consequently, real diverse criteria can be set together with exact data and/or human judgment in order to build an AHP model, and form a unique inclusive picture of, with a model solution, to the problem. An AHP model has its limitations when there is a non-trivial dependency among elements, so the new structure cannot be simply processed by standard AHP approach (Mls and Gavalec 2009)

ANP is a generalised form of AHP that can capture interdependent relationships in the decision-making process by relaxing hierarchical and unidirectional assumptions. In essence, a hierarchal model is a special case of a network-based model and measures tangibles and intangibles (Saaty 2005).

In ANP, like AHP, pair-wise comparisons are used to prioritise the elements; however, unlike AHP, comparisons are not just performed between elements at the same hierarchical level but as a network.

4. Holonic RMS architecture and the AHP/ANP

In this section, an essential contextualisation of holonic architecture and AHP/ANP is provided to facilitate the conceptual recognition for their integration towards RMS performance evaluation.

4.1 *Holonic concept and RMS*

HMS have been introduced to cope with a rapidly changing environment using a modular mix of components (holons). The concept of holon originated from Koestler (1989) who described holon as the hybrid nature of sub-whole/parts in real life systems. Holonic manufacturing has been developed from Koestler's concept, which was originally introduced to social organisations and living organisms. A holonic MS is designed on the basis of autonomy and co-operation of holons for creating flexible behaviour to adapt to changing production conditions. To date, the holonic concept has been focused on developing architecture for planning and control functions required for managing existing production systems at the machine level such as the conceptual migration strategy developed by Chrin and McFarlin (1999).

A holonic structure based on the basic holons blocks proposed by Van Brussel *et al.* (1998) can be developed for RMS. A structure based on a typology of manufacturing system elements (products, resources, orders), along with roles and behaviours for these manufacturing control elements, are developed by Blanc *et al.* (2008). In addition to common characteristics found in HMS, such as distribution, autonomy, interaction, other characteristics such as reconfiguration, customisation and hybridation (hierarchical relationships and peer–peer relationships) can be obtained (Zhang *et al.* 2003).

4.2 *Holonic architecture and AHP for RMS performance evaluation*

Holons can belong to multiple hierarchies or form temporary hierarchies, and more importantly do not rely on specific operations in the hierarchy (Van Brussel *et al.* 1999). According to the basic building blocks of a HMS and their horizontal and vertical self similarity of components with similar behaviour (Van Brussel *et al.* 1998), a hierarchical structure can be obtained to reduce complexity of the system behaviour. Accordingly, complex architecture could be transformed into fundamental components of the

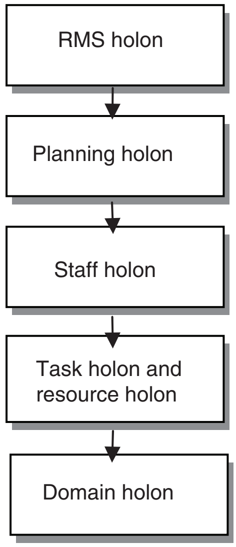


Figure 2. RMS holon hierarchy.

hierarchical levels, i.e. similar to a decision problem hierarchy proposed by Saaty (1980) and Saaty and Vargas (1990). Accordingly, as shown in Figure 2, a hierarchical structure for holonic RMS structure can be obtained by breaking holons into hierarchical levels as follows:

Level 1: RMSs holons (alternative configurations/manufacturing system).
Level 2: Planning holons (planning horizons when the RMS strategy is being sought).
Level 3: Staff holon (decisive actors, managers, operators).
Level 4: Task holons (processes, operations, products family formation) and resource holons (manufacturing facilities, machines, tools, computer software and hardware).
Level 5: Alternative and domain holons.

AHP structure could reflect a hierarchical top-down holonic structure, in which horizontal self similarities occur among the components at each level. The architecture could be designed from the product viewpoint or the process viewpoint, and the levels can be adjusted accordingly. Each holon at each level could have a hierarchy of its own sub-holons.

Based on identical levels to those mentioned above, a design strategy for manufacturing system choices was developed via an AHP model in the authors' previous work (Abdi and Labib 2003). A few research works have been undertaken to link the holonic hierarchical architecture to AHP. Pujo and Ounnar (2008) developed a holonic manufacturing architecture towards an AHP model, which presented hierarchical criteria system and corresponding indicators to be jointly analysed with respect to various interests of interacting holons. The typical AHP model consisted of alternatives (products in the queue), and criteria including work in process (WIP), production cost and queuing time. Similarly, this paper develops a systematic linkage between holonic architecture and AHP/ANP. In contrast, the proposed ANP model allows interactions among the key elements, including related factors to process reconfigurability, which could affect

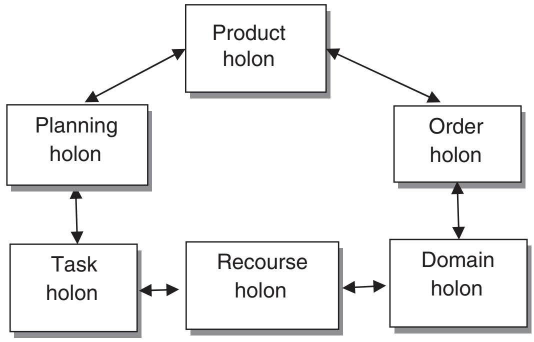


Figure 3. RMS holonic network.

RMS performance. In addition, unlike a typical AHP/ANP model, the model is not intended to find an alternative solution, but to explore critical performance factors. Finally, pair-wise comparisons are performed between all the applicable elements (as input to the model) and pair-wise analysis is performed for a meaningful pair of critical elements (as the output of the model).

Similar to holonic architecture in which holons are structured based on self-similarities, all the elements of each level in AHP contain similarities in common and are compared with respect to the corresponding upper level element(s). However, the hierarchical structure reflecting the holonic structure faces the following shortcomings:

- Restrictions of relationships among elements at each level to only the next higher/lower/level element.
- There are no interactions among elements at the same level.

Desired network structure cannot be processed by the standard AHP approach, potentiality ANP could stand for modelling such decision evaluation situations (Mls and Gavalec 2009). To overcome the above limitations the ANP theory can be applied for structuring the RMS evaluation as described in the next section.

4.3 *Holonic RMS and the ANP*

The framework for holonic manufacturing proposed by Van Brussel *et al*. (1998) could be developed and adapted to achieve a holonic RMS consisting of interacting holons with dependencies as demonstrated in Figure 3. Planning holons might be planning horizons, a planning team or planning actors, products ranged in the production planning, or product families' formation within reconfiguration link, which were introduced by the authors (Abdi and Labib 2004). Task holons include manufacturing operations to cope with capacity and functionality required for products in production range in planning horizons. Resource holons include equipment, machines, tools, multi-directional conveyers, layout configurations, and operators. Domain holons limit resource holons in order to be feasible and manageable. Therefore, alternative holons such as alternative resources, alternative product families or alternative manufacturing processes could act as domain holons and should be economically and operationally feasible. Facilitator holons can also be added to the architecture at each holon at each level in order to allow corresponding holons to ease the decision against lower level holons. This will create some kind of flexibility for each main holon to play its role in decision making over the RMS holon.

The framework can then be transformed into an ANP model in order to reflect a heterarchical holonic structure, in which horizontal/vertical self similarities occurred among the interacting components in the network.

5. The proposed ANP model for RMS performance evaluation

In this section, the ANP is employed as a multi-criteria analytical approach to evaluate RMS performance. Influencing elements are grouped into clusters, which would contain their relevant components. Clusters and their components might have interactions with each other, either within a cluster (inner dependency) or even between the elements within different clusters (outer dependency). Figure 4 demonstrates a flowchart of the ANP modelling and analysis steps.

The proposed ANP model is built up through using the SuperDecision software (SuperDecision 2009) as shown in Figure 5.

The model consists of six clusters representing six groups of performance components (holons), where each one can consist of different sub-elements (sub-holons). Clusters and

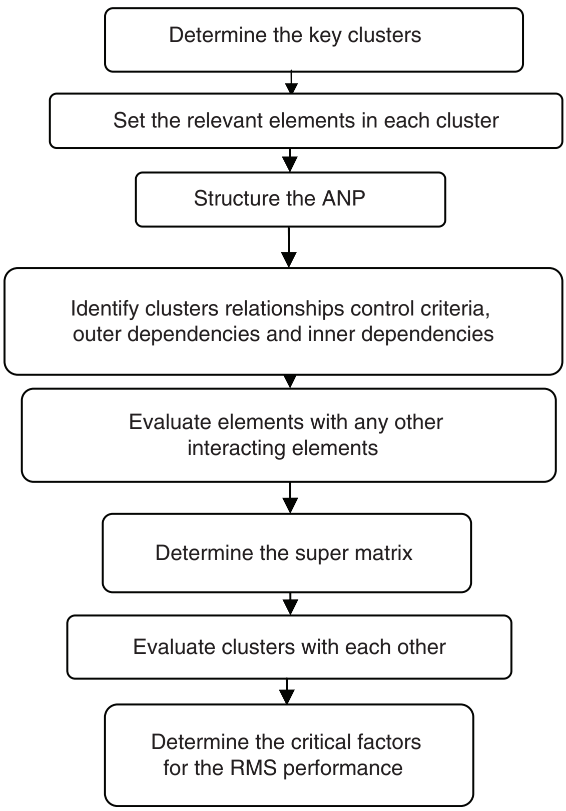


Figure 4. Flowchart of the ANP steps for RMS performance evaluation.

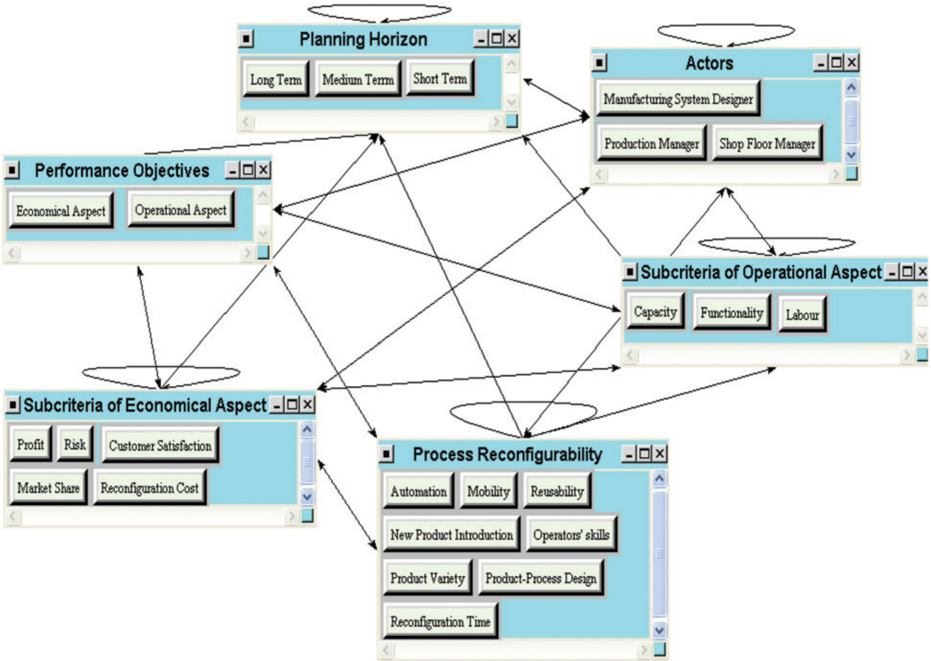


Figure 5. The proposed ANP model for RMS performance evaluation.

their element along with their outer dependencies and/or inter dependencies are described as follows:

Cluster (a). Planning horizon

Planning horizon can be broken down into a number of time periods in order to reduce uncertainty and risk caused over a long variable period. However, unlike the traditional hierarchical planning levels, those periods could have interactions against each other, and one can have an effect on, or contribute to, the other planning terms. Consequently, three planning periods of short term, medium term and long term for RMS evaluation are identified.

Cluster (b). Actors

Human expert as a holon can be linked to HMS in order to enhance the decision making process for achieving optimal system performance (Kotak *et al.* 2003). Correspondingly, considering input data from managers/experts at different levels, plant manager(s), shop floor manager(s), and manufacturing designer(s) are recommended as the decisive actors.

Cluster (c). Performance objectives

The main objectives for RMS evaluation are grouped in two categories: economical aspects and operational aspects. Each category is then taken apart into an individual cluster with the relevant elements as explained in the next sections.

Cluster (d). Sub-criteria of economical aspect

This includes the financial elements of customer satisfaction, market share, reconfiguration cost, profit, and risk. The underlying challenge for the cluster would be whether it is possible to perform high reconfigurability with low effort in terms of cost and time.

Cluster (e). Sub-criteria of operational aspect

The cluster is mainly involved with flexibility in capacity and functionality over configuration stages. Capacity as 'maximum production rate available', and functionality as the operational degree of switching from a product to the other with different process requirements, and labour including operators and engineers are considered to enhance process reconfigurability. Elements are evaluated among themselves as well as with respect to the relevant elements in the other clusters, particularly in the process reconfigurability cluster such as reconfiguration time/cost, new product introduction and product variety.

Cluster (f). Process reconfigurability

Process reconfigurability consists of different elements, which can specifically be found as distinguishing features of RMS. Elements of automation, mobility reusability, new product introduction, product variety, product-process design and reconfiguration time are evaluated within the cluster and also with the other elements in different clusters, particularly in the clusters of sub-criteria of economical aspect and sub-criteria of operational aspect.

6. A case study

The ANP model is examined through a case study in company A, which is a US-based company and a global supplier of a broad range of modules and components to the motor vehicle industry. The manufacturing plant in the UK produces around 2000 similar product variants for different car industries. The data was collected from the decisive managers along with the authors through pair-wise-comparison based questionnaires and then transformed into the ANP preference matrices. The participants were asked to compare two performance elements with respect to another influencing factor in the network using a 9 point scale ranging from 1 (no preference) to 9 (high preference). The quantitative financial data such as sales and market share derived from the statistical sources in the company is also used to check the response validity for the applicable parameters. Furthermore, the possible missing data (no comparisons specified) and/or subjective issues, mostly reflecting on high inconsistencies over the pair-wise comparisons, are revised and moderated by the authors in order to aid demonstration of the complete ANP implementation.

Company managers in different levels participated in evaluation of the key performance parameters. The shop floor manager provided reliable technological based performance evaluation over operational aspects, whereas the plant manager provided strategic/tactical reliable financial performance parameters such as sales, market share and profit. A partial sample of the questionnaire asking the comparison of automation and other elements in process reconfigurability cluster is demonstrated in Table 1.

As shown in Table 2, the six clusters are compared with each other with respect to their influences on the RMS performance. When there is no inter dependency, the rating

Table 1. A partial sample of the questionnaire for automation in the process reconfigurability cluster.

1.	Automation	>=9.5	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	Mobility
2.	Automation	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	>=9.5	No comp.	New Product Introduction
3.	Automation	>=9.5	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	Operators' skills
4.	Automation	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	**6**	7	8	9	>=9.5	No comp.	Product Variety
5.	Automation	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	>=9.5	No comp.	Product-Process Design

preference of a cluster with itself is equal to zero. Otherwise, with having incurred an inter dependency in a cluster such as actors and planning horizon, a non-zero value can be derived from the clusters evaluation.

Figure 6 illustrates the clusters of greater magnitude over performance. The clusters are not fully independent from each other as their elements might have interactions with the other clusters' elements. For example, performance objectives cluster possesses relations with two clusters of sub-criteria of operational and economical aspects. Similarly, process reconfigurability and sub-criteria of operational aspect interact with each other.

As shown in Figure 7, the ratings of the elements of process reconfigurability can be obtained from overall synthesised priorities and the super matrix. The preference values could be in three different modes: ideal, normal, and raw. The raw values are directly obtained from the super matrix, ideal values are the raw values multiplied by the cluster weight, and the normal values are obtained by normalising ideal values as to sum up to 1.

As shown in Figure 8, the rankings for all elements are calculated in terms of normalised values by clusters and limiting values which are the overall ranking considering all interactions among the element and the clusters.

As shown in Figure 9, criticality degrees of the influencing elements with respect to the two planning horizons of long term and short term are presented. Most of the elements have a low impact on the RMS performance over the long term and the short term plan. For example, reconfiguration time has a high impact on the RMS performance in the short term, but a medium impact the over the long term. It might be because of the fact that in the long term, reconfiguration time could be dealt smoothly with a stable short time while switching a product to the other product. In contrast, reusability significantly affects the RMS performance over the long term plan whereas it has a low impact on the system performance in the short term. In the company, there is no common highly critical element which could significantly affect the system performance in both planning terms.

As shown in Figure 10, the elements towards the co-ordination centre such as reconfiguration time have the slightest impact on the economical performance and the operational performance in the case study. On the contrary, the elements towards the top right corner have high influence on the economical aspect as well as the operational aspect.

Table 2. Clusters rating matrix.

Cluster node labels	Actors	Performance objectives	Planning horizon	Process reconfigurability	RMS performance evaluation	Sub-criteria of economical aspect	Sub-criteria of operational aspect
Actors	0.117486	0.045730	0.090232	0.060711	0.000000	0.113282	0.030340
Performance objectives	0.232555	0.000000	0.000000	0.158322	0.800000	0.234929	0.331593
Planning horizon	0.046207	0.111361	0.244929	0.162087	0.200000	0.102017	0.162060
Process reconfigurability	0.068237	0.145557	0.000000	0.163355	0.000000	0.101387	0.171902
RMS performance evaluation	0.335736	0.355078	0.664839	0.000000	0.000000	0.000000	0.000000
Sub-criteria of economical aspect	0.104201	0.177325	0.000000	0.039149	0.000000	0.370129	0.121157
Sub-criteria of operational aspect	0.095579	0.164949	0.000000	0.416375	0.000000	0.078257	0.182948

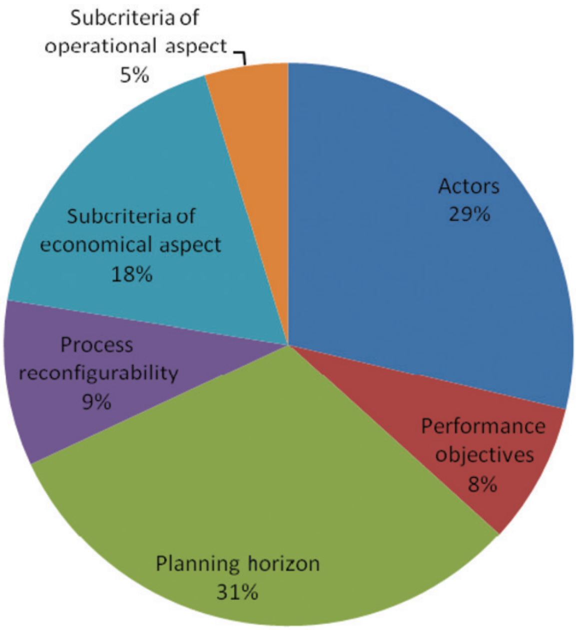


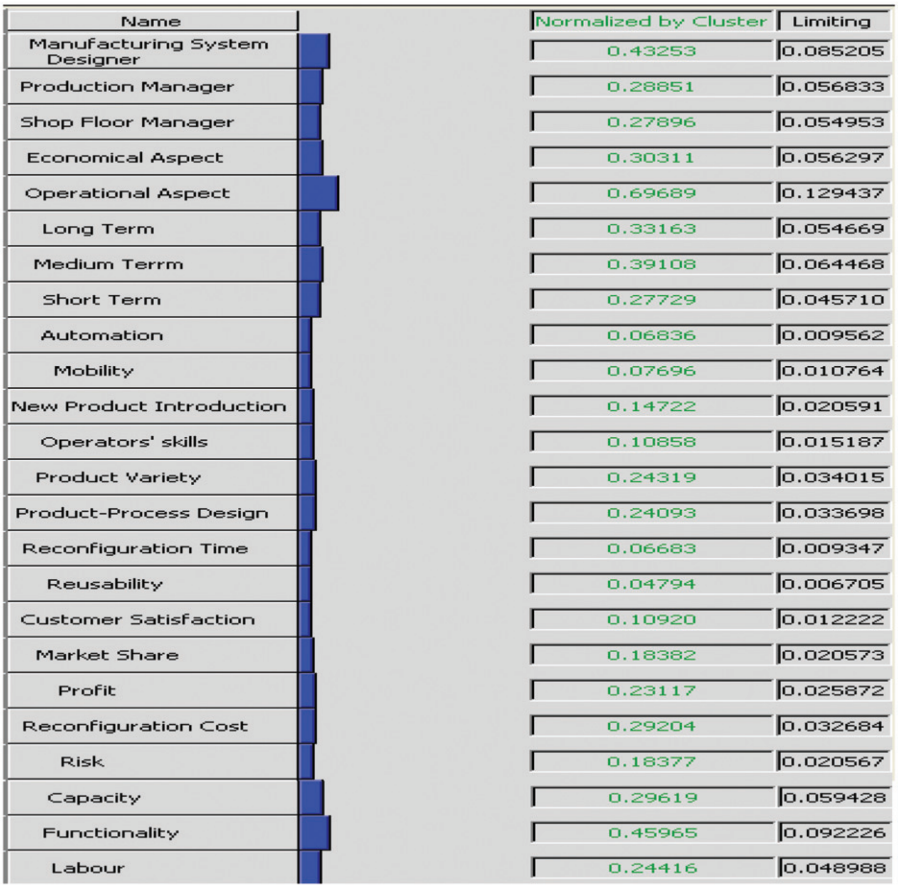
Figure 6. The relative weight of the ANP clusters.

Name	Graphic	Ideals	Normals	Raw
Automation		0.243449	0.062422	0.007613
Mobility		0.322589	0.082715	0.010087
New Product Introduction		0.584672	0.149915	0.018282
Operators' skills		0.399801	0.102512	0.012502
Product Variety		0.951386	0.243944	0.029749
Product-Process Design		1.000000	0.256409	0.031270
Reconfiguration Time		0.237828	0.060981	0.007437
Reusability		0.160299	0.041102	0.005012

Figure 7. The preferences of elements in the process reconfigurability cluster.

The other key elements might have medium priority on both aspects such as capacity, or high impact on one of the two aspects. For the company, there are no highly mutual critical elements with respect to both the economical performance and the operational performance. However, it does not mean that performance monitoring the other elements in the network could be neglected.

As shown in Figure 11, reconfiguration time plays a key role in the RMS performance with respect to capacity and functionality. Therefore, any improvement towards reconfiguration time reduction could significantly affect the RMS performance in terms of capacity and functionality. The other element, not far from the highly critical region is reusability which has relatively greater impact on capacity compared to functionality.



Name	Normalized by Cluster	Limiting
Manufacturing System Designer	0.43253	0.085205
Production Manager	0.28851	0.056833
Shop Floor Manager	0.27896	0.054953
Economical Aspect	0.30311	0.056297
Operational Aspect	0.69689	0.129437
Long Term	0.33163	0.054669
Medium Terrm	0.39108	0.064468
Short Term	0.27729	0.045710
Automation	0.06836	0.009562
Mobility	0.07696	0.010764
New Product Introduction	0.14722	0.020591
Operators' skills	0.10858	0.015187
Product Variety	0.24319	0.034015
Product-Process Design	0.24093	0.033698
Reconfiguration Time	0.06683	0.009347
Reusability	0.04794	0.006705
Customer Satisfaction	0.10920	0.012222
Market Share	0.18382	0.020573
Profit	0.23117	0.025872
Reconfiguration Cost	0.29204	0.032684
Risk	0.18377	0.020567
Capacity	0.29619	0.059428
Functionality	0.45965	0.092226
Labour	0.24416	0.048988

Figure 8. Normalised and overall priorities for the network elements.

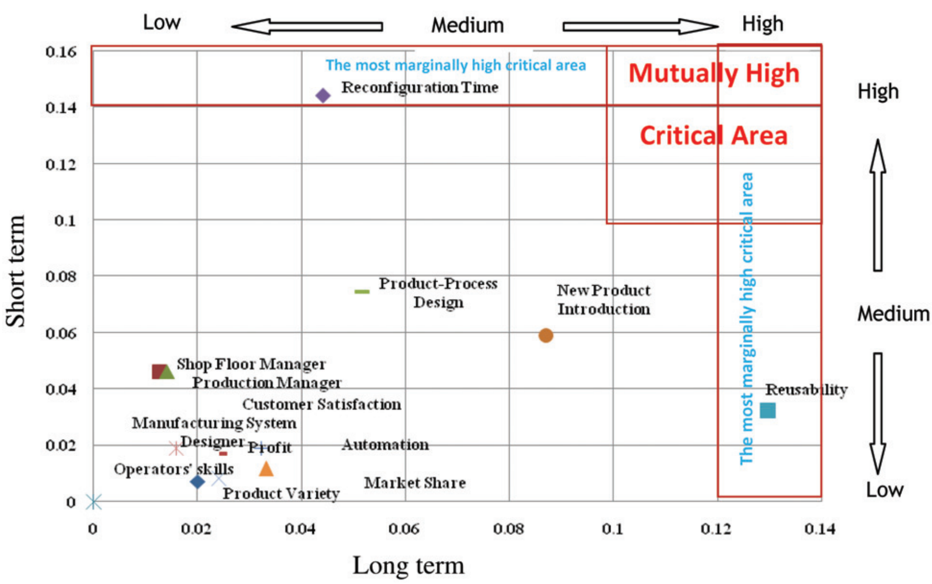


Figure 9. Criticality of the network elements with respect to long term plan and short term plan.

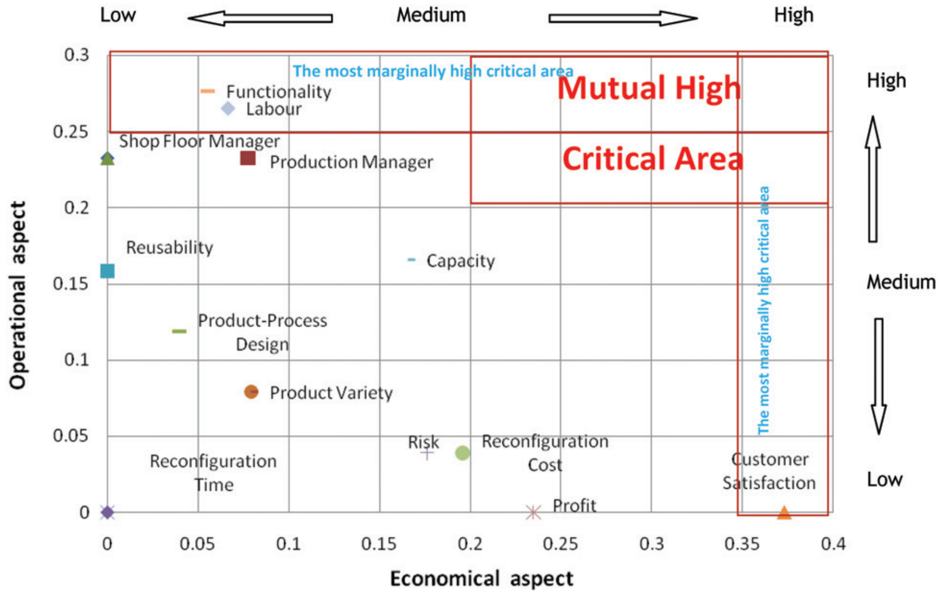


Figure 10. Criticality of the network elements with respect to economical aspect and operational aspect.

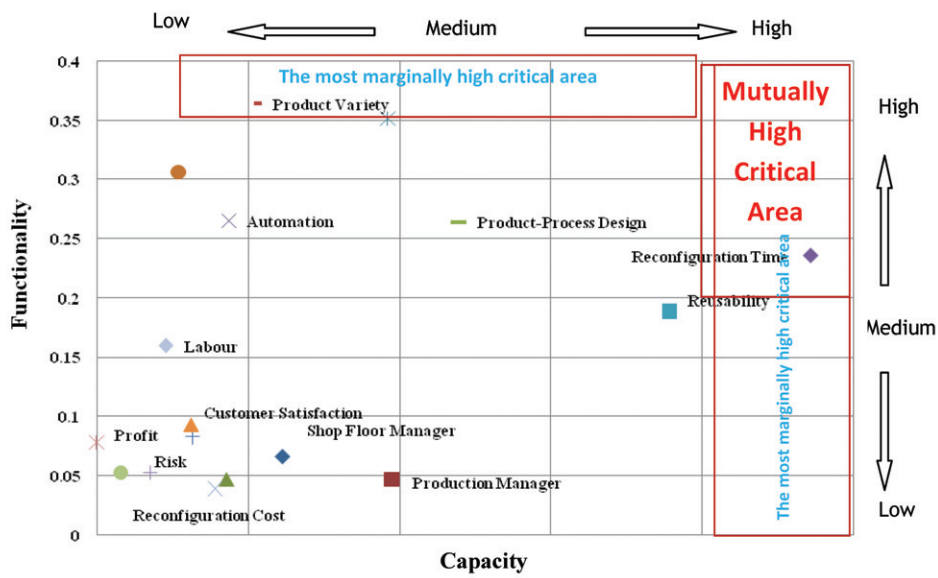


Figure 11. Criticality of the network elements with respect to capacity and functionality.

7. Conclusion

Holonic architecture for RMS is developed to reflect the key elements influencing the system performance. This is then transformed into a hierarchy of holons, which builds groundwork for an AHP/ANP model in order to properly reflect the RMS elements in interactions for performance evaluation. The proposed ANP model is capable of linking technological and economical factors are grouped in different clusters and demonstrated through an industrial case study.

The results show that reconfiguration time and reusability for both capacity and functionality are highly critical. Therefore, those elements must be carefully optimised as any disruption in the performing elements cause enormous impact on the system performance, particularly on process reconfigurability.

The findings of the study must be cautiously interpreted. The data is involved with dependent parameters rather than independent parameters, and mostly come from the company managers rather than the statistical values of dependent/independent variables. The actors must simultaneously compare numerous criteria with respect to a different parameter, and possibly in a different cluster, and might fail to differentiate the preferences. Therefore, the performance measures might be subjective and could lead to bias results. In addition, distinction between positive or negative influences of performance factors on the parameters under evaluation must be taken into account.

Although the ANP proposed model consists of different planning horizons, which help considering time-variant performance, it is not a dynamic evaluation model. Therefore, the proposed model can be developed and remodelled dynamically by introducing time-dependent elements that facilitate supplementary trade-offs. This will enable the RMS to respond to the unpredictable changes continuously and effectively over time. In addition, as the influencing values might be vague in reconfigurable environments, the inner/outer dependencies can be characterised by applying fuzzy sets. Therefore, the synthesised results can then be assessed in the fuzzy range of the network fuzzy elements.

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