Risk and decision analysis for Reconfigurable Assembly System Design under uncertainties

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ABSTRACT: *To face the variable demand of the market, modular and mobile equipment are integrated on production lines. Previous works proposed design and evaluation methodologies to build reconfigurable production systems. However, taking the right decision concerning investments and the choice of equipment may be complex. In this paper, we present RAS design from a risk and decision analysis perspective to support decision making. Market demand scenarios are associated with occurrence probabilities. A decision tree represents consecutive scenarios, for which the decision maker is proposed to make a choice regarding investments for the assembly line. The utility function is computed based on the decision makerâs attitude to risk. The objective function computing the final score of a scenario and a decision covers investments, reconfigurability rate and performance of the system. Implications of early investments towards reconfigurability can be identified. The approach is applied on a real use case from the automotive industry.*

KEYWORDS: *Changeability, Reconfigurability, Reconfigurable Assembly System, Decision Support Tool, Decision analysis*

1 INTRODUCTION

To face a volatile and unpredictable customer demand, developments of a new generation of production systems, Reconfigurable Manufacturing and Assembly Systems (RMS and RAS), have been carried out. (Koren et al., 1999) formalized the paradigm of reconfigurability in Production Systems (PS), and defined six core characteristics of production systems: scalability, modularity, integrability, customisation, convertibility and diagnosability.

Fluctuations of the market imply the need of a production system able to follow changes in terms of product type or production volume. Depending on the economical context, companies need to quickly configure and set adjustment parameters of the system. In order to achieve these quick changes, RMS and RAS integrate modular tools and machines, and easily movable equipment (Beauville dit Eynaud et al., 2018). An important point is also to integrate consideration of changeability at early stages of production system development (Andersen et al., 2017). Companies are not familiar with changeable systems and research works focus on supporting the industry in the process of RMS integration. Furthermore, decision makers struggle with the evaluation of new generation PS on criteria which are hardly comparable on a same scale. Indeed, the comparison of performance metrics with reconfigurability indicators is questionable. We aim to support RMS Design by answering the question of how to invest and adjust in the best way the production system.

During the PS life-cycle, the economical context will change. In this paper, the demand is modeled by scenarios, for which are periods of time are corresponding to a market requirement, for which a configuration has to be selected. In the proposed Reconfigurable Production System Design Problem (RPSDP), consecutive scenarios are considered, and implications of early decisions in a previous scenario are taken into account in next scenarios. In this paper, a "scenario" corresponds to the succession of a decision step followed by a market evolution (event). The problem to solve is the choice to invest or not in a new resource for each time period, without knowing with certainty how the market will change.

2 STATE OF THE ART

2.1 Decisions in reconfigurable production systems design

Previous research focused on providing support tools for companies to choose appropriate resources and PS configuration in the design process. (Andersen et al., 2017) and (Beauville dit Eynaud et al., 2020) proposed RMS/RAS design methodologies, covering design steps from needs identification to final decision.

In order to support the design process, reconfigurability metrics have been investigated and developed based on the six core characteristics of reconfigurability (Wang et al., 2017; Rösiö et al. 2019; Beauville dit Eynaud et al., 2020). In particular, (Beauville dit Eynaud et al., 2020) defined quantitative metrics for reconfigurability evaluation of RAS, and compared obtained metrics with performance indicators evaluated by discrete event simulation (DES). Results are then made available on a dashboard for the decision maker.

However, during the design procedure, the company needs to evaluate various technical solutions (for example fixed, movable or mobile robots), several layout configurations, and different demand scenarios. Then, based on metrics evaluated for all these cases, a decision has to be taken. The decision maker faces many indicators with a complex imbrication: if a technology has been adopted in a first investment step, this decision will have consequences on investment decisions in the next steps, that is to say in the next scenarios. The problem can be modeled using a tree structure, where each node corresponds to an investment decision or to an event (market change).

2.2 Risk decision analysis

Decision analysis supports judgement in the case of complex, multi-criteria and multi-stages scenarios. It enables an objective, mathematical-based decision instead of a bias-distorted decision when conducted without methodology (Tversky and Kahneman, 1974). Risk decision analysis covers the study of alternatives, influences between parameters and their prioritisation. The scope of decision analysis is wide and covers the economic sphere, risk analysis in engineering, medicine, etc.

In the domain of floating production storage and offloading units, (Lassagne, 2000) studied the impact of the integration of risk-reduction measures on offshore installations on both technical and economical sides.

In the automotive sector, (Tchoffa et al., 2012) applied decision analysis on the management of industrial incidents. With their model, authors are able to evaluate the impact of the different incident causes, their inter-relations and their probabilities of occurrence.

The methodology to model a decision problem in an uncertain environment is the following (Clemen and Reilly, 2013):

1. Identification of the situation and objectives
2. Identification of alternatives
3. Problem modeling
4. Determination of the best alternative
5. Sensitivity analysis

The decision maker's attitude to risk is evaluated based on equivalent lotteries which enables to define the utility function. The principle of an equivalent lottery is to give the choice between two lotteries: for example, winning a high gain with 10 % chance and not winning at all with 90 % chance, or winning a small gain with 50 % chance. If the decision maker chooses the second lottery, he is risk-averse. In the case of conflicting objectives, the equivalent lotteries also support the definition of the multi-attribute utility function based on the company's priorities.

In the problem modeling step, an influence diagram is built to represent in a formal way decisions, uncertainties, values and inferences. It is an oriented acyclic graph with decision nodes and value nodes (deterministic nodes) (Clemen and Reilly, 2013). The influence diagram is an extension of Bayesian networks, as the nodes of the graph correspond to probability distributions and arcs between nodes to dependencies between those distributions. The decision tree is then built to represent the sequentiality of decisions and events in an explicit way. A decision tree is an oriented graph with uncertainty nodes, decision nodes and terminal nodes.

The resolution process is decomposed in two steps, with the objective to maximise the expected value of the profit (Goodwin, 2004). Using the decision tree, in the roll-forward step, the final payoffs of each alternative, corresponding to a branch of the decision tree, are calculated. Then, the rollback step consists in the computing of the profit value for each terminal node. The chosen decisions are the ones with the highest expected values.

2.3 Conclusion of the literature review

In a volatile environment, it is complex to take objective decisions regarding investments. Furthermore, decision makers can be influenced by a bias regarding new technologies: mistrust or on the contrary blind trust.

The industry needs a decision support tool for the design of RMSs and RASs. Previous works fixed design methodologies and evaluation criteria to help design and rating of the integration of new technological solutions or configurations of the production system. However, the quantity of parameters to take into account while conceiving a manufacturing system (performance, reconfigurability, and costs metrics) makes the decision process complex. In addition, it is complex to have a clear overview of consequences of consecutive decisions over scenarios. By modeling uncertainty about future market trends, it is possible to simulate the system evolution following consecutive decisions.

Decision makers need an overview over market demand scenarios supporting multi-criteria evaluation of decisions.

3 DECISION ANALYSIS FOR RAS DESIGN

3.1 Case study: Multi-product assembly line

The case study is a multi-product engine assembly line in the automotive industry, facing a varying demand in both product mix and volume. To face changing market requirements, the new strategy of the company is to transform its production system into a RAS. However, taking decisions in this context is complex. Indeed, decision makers are not familiar with the new reconfigurable equipment, and in addition, the production system seeks contrary goals: being efficient, as well as rapidly reconfigurable and economically interesting.

The objective is to maximise the utilisation rate of machines, minimise investments and maximise reconfigurability of the system.

Alternatives offered to the decision-maker are, at the beginning of each scenario, to choose to invest in a new resource, or to abstain from investing. Each resource type has a different price, reconfigurability rate and utilisation rate. This last parameter is determined by running the same scenarios in a Discrete Event Simulation software, enabling assessment of the performance of the production system with the new machine. The price of resources is also known, and the reconfigurability metric of each resource is computed by means of the formula defined in (Beauville dit Eynaud et al., 2020), based on reconfigurability characteristics defined by (Koren et al., 1999).

In this study, we propose two scenarios for the variations of the market demand: an increase and a decrease of the demand.

3.2 Model

The approach is implemented in the decision analysis software Decision Programming Language (DPL9) developed by Syncopation. The utility function is determined by equivalent lotteries generated with ASSESS tool. The user indicates the attributes (decision parameters) of the problem, boundary values, and the tool supports the determination of the multi-attribute utility function. In this problem, the four attributes are the investment level, the machine utilisation rate, the reconfigurability indicator and the maturity indicator. The maturity metric depicts the level or readiness of the proposed technological bricks.

Figure 1 depicts the influence diagram built in DPL9. Two scenarios are represented. The squares correspond to decision nodes, ovals to chance nodes (events) and squares with rounded edges are value nodes. Arrows between nodes represent influences between them. The model includes two consecutive scenarios. At the beginning of a time period, a decision regarding purchasing of new resources is taken by the company. Then, a scenario run is materialized by the realisation of a market evolution. The same procedure occurs a second time to illustrate the second scenario.

The decision tree of the problem is symmetric. The four decision alternatives are illustrated Figure 2: no investment (no action), add a fixed robot, add a movable robot, or add a mobile robot.

A chance node can lead to four possibilities: strong market decrease, low decrease, low increase or strong increase of the demand. In the first scenario, depicting a rise of the market demand, the probability of strong decrease is 0 %, the probability of low decrease as well as low increase are 40 %, and the probability to face a strong increase is 20 %. The second scenario simulates a decline of the demand, and is modeled by a 70 % chance of strong market decrease, 30 % chance of low decrease and 0 % of chance of increase (for both low and strong possibilities).

3.3 Results

Figure 3 presents an extract of the decision tree after DPL9 simulation. Considering given probability distributions and values for the attributes, the multi-attribute utility function is maximised when a movable robot is added to the system in the first time period, and no investments are done in the second period.

Indeed, in the first scenario, the market evolution is uncertain and is likely to increase or decrease. This explains why it is relevant to integrate on the line a resource which can be easily added or removed. In the

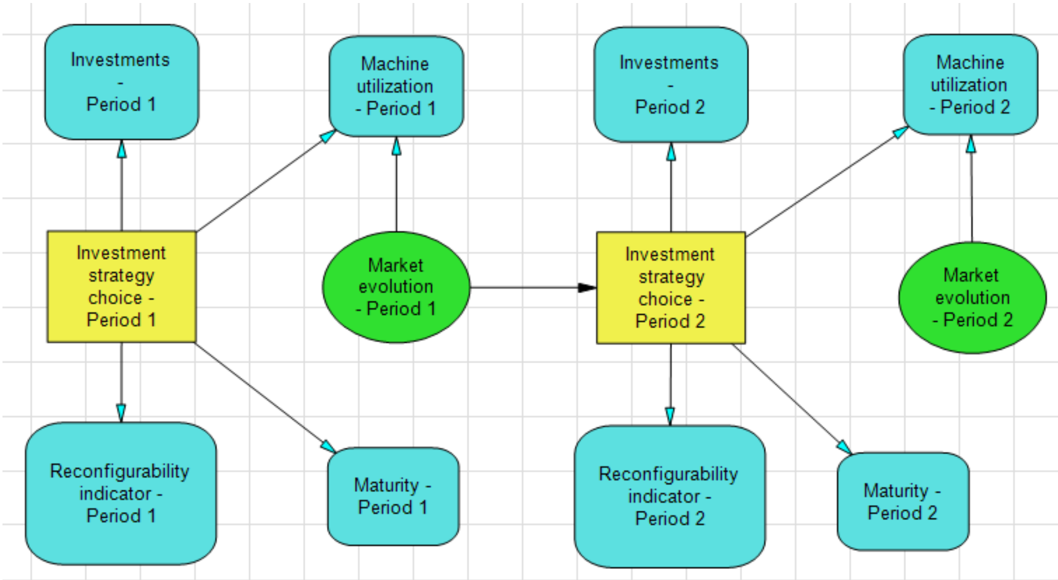

Figure 1 – Influence diagram (DPL9)

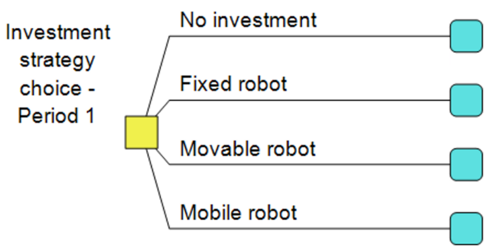

Figure 2 – Decision node (DPL9)

second period however, a decrease is certain, and it is preferable not to increase unnecessarily the capacity of the system.

In the second scenario, the decision analysis suggests to add fixed resources on the engine assembly line. Indeed, as the demand increase is quite certain, the most reasonable choice is to invest in resources for a long-term high-throughput production.

In a second step, a sensitivity analysis is conducted to verify the robustness of the solution regarding input parameters. In this paper, we propose to conduct a sensitivity analysis on the maturity indicator of the mobile robot. For now, the value of this metric is $M_R = 0.48$. The hypothesis we want to verify is if the increase of M_R has an impact on the final decision proposed by DPL9. Figure 4 shows the results of the sensitivity analysis. The abscissa corresponds to the value of M_R for the mobile robot, and the ordinate is the expected value. From this graph, we can read that above a value of 0.6 for the maturity index, there is a policy change in the model, and the solution ”mobile robot” will be preferred.

3.4 Discussion

The contribution of decision analysis for RMS/RAS design concerns decision support in an industrial context where companies are divided between the urge to integrate new components to have state-of-the-art production facilities, but are limited by the high price of flexible solutions. We propose an approach to enable statistically-based objective decision in an uncertain environment.

The specificity encountered when designing a reconfigurable system is the inability to predict exactly sales and the need to assess the transformability potential of the line. Thus, expected production volumes and product mix can be formulated as scenarios defined by probabilities of occurrence. We are able to build a model taking into account the three axes to evaluate a reconfigurable system : costs, performance and reconfigurability.

Influence diagrams and decision tree are efficient tools to represent and communicate on various scenarios. They give a clear overview on relationships between decisions, events and relevant values, and illustrate at one sigh all possible alternatives.

Results obtained in this study are promising and give a new insight in the RMS/RAS design process. By enabling a sensitivity analysis on one of the input criteria, such as the maturity of a type of resource, this approach supports the industry to evaluate the right moment when to invest in a new type of resource. This way, the method helps the upgrade of production facilities regarding Industry 4.0.

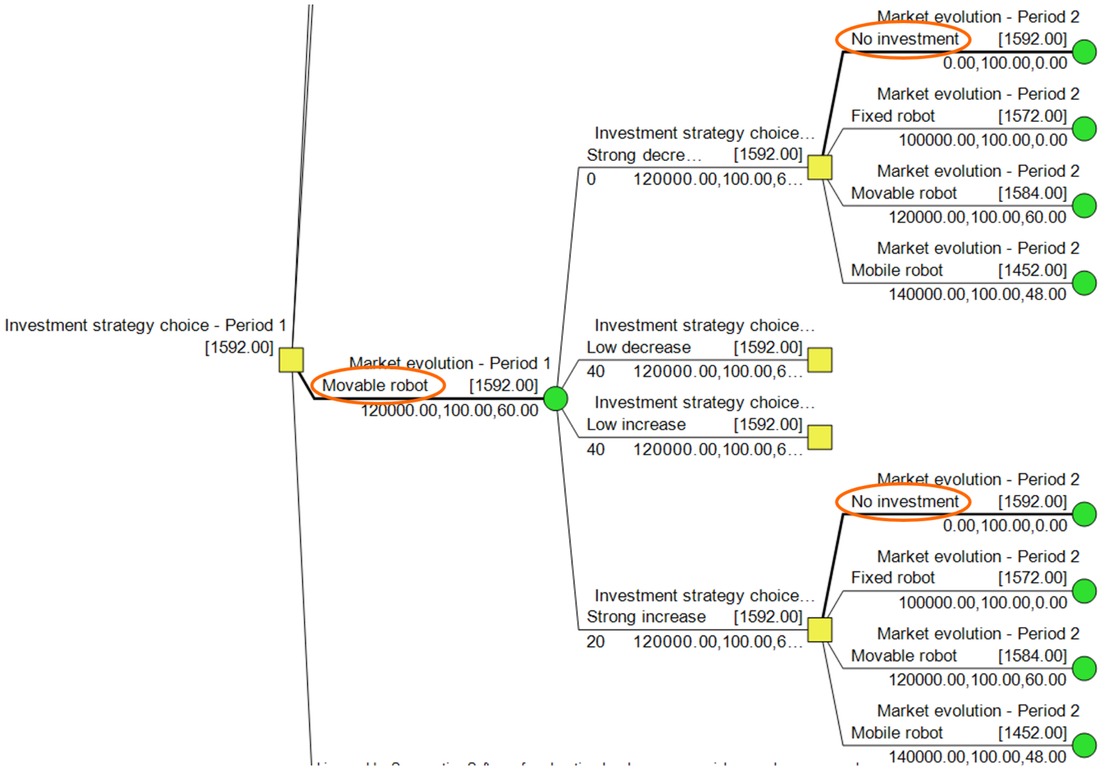

Figure 3 – Proposed alternative

4 CONCLUSION

In this paper, we propose the application of decision analysis on the RPSDP. The utility function is built based on the parameters of the RMS/RAS, which are the reconfigurability, the productivity and the investment cost of the system. The attitude towards risk of the decision maker and the relative weights of the attributes are obtained by evaluation of equivalent lotteries. For the studied production scenarios, occurrence probabilities are defined and validated by experts. Based on this data, and by applying decision analysis on the RPSDP, we obtain a suggestion for the design strategy.

Our methodology provides an evaluation of many parameters of the problem, and aims to erase psychological bias in the design process. Furthermore, the summation of all relevant data and scenarios in a single decision tree supports communication in decision meetings.

The tool used for decision analysis is currently independent of other modules of the approach. Further research will focus on the automation of the analysis, by implementing gateways between the reconfigurability indicators calculation module, the DES software, optimisation module, and the risk decision analysis software.

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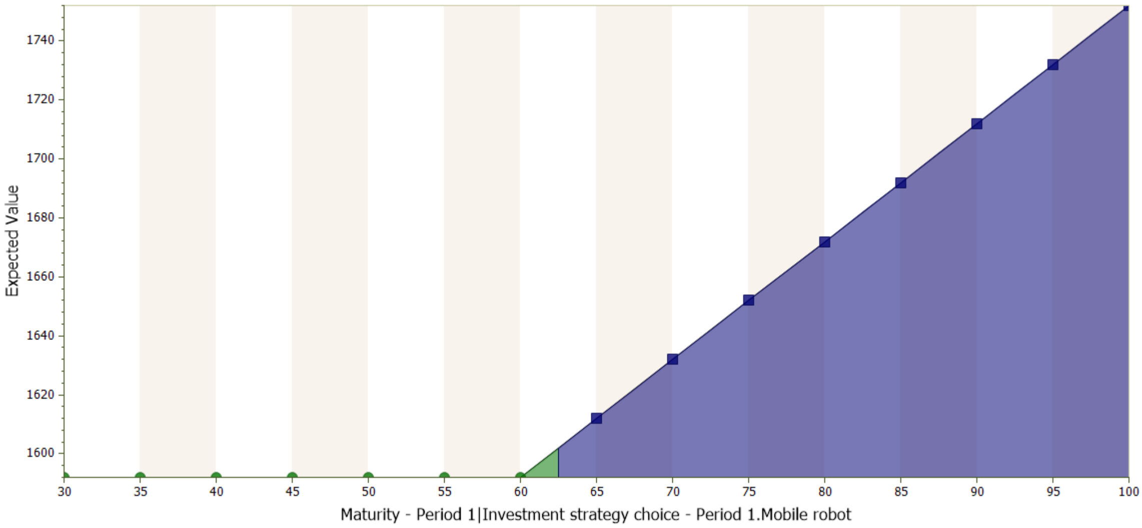

Figure 4 – Result of the sensitivity analysis

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