MACRO-REACHABILITY TREE EXPLORATION FOR D.E.S. DESIGN OPTIMIZATION

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Abstract

Discrete event systems, such as manufacturing facilities or logistic systems, can be improved by the optimization of their models, which can be based on the exploration of the reachability tree (RT) of the Petri net (PN) used to model them. Thanks to this technique it is possible to obtain a sequence of decisions that leads to an optimal behaviour of the system, according to one or several cost or benefit functions and a set of restrictions. Sometimes the original system is not completely defined, since it contains some undetermined parameters, and then several decisions should be taken in order to assign precise values to all these parameters, and so to define the system in a right way. These decisions can be seen as design-decisions(the location of warehouses of a logistic system or the number, the type and distribution of machines, manufacturing cells, transport devices and products storage of a manufacturing facility can be considered, etc.), different from the decisions taken in order to optimise the behaviour of a determined system, which could be seen as operation-decisions. Those design-decisions could lead to completely different systems, related to diverse models, in this work based on PN. Each one of these PN has associated a specific RT, which can be explored and provide particular solutions. This paper describes and explores a general method to afford this kind of problems. The technique is based on the concept of macro-RT, built up from the different RTs related to the different PN solutions of the considered decision making procedure. The aim is to present a systematic treatment of the optimization process of certain problems related to models based on PN, by means of the exploration of a macro-RT, as well as to show some application examples of this technique to manufacturing processes.

Keywords: Modeling & Simulation (M&S), Discrete event systems (DES), Petri nets (PN), Reachability tree, Design optimization.

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1 Introduction

The optimization of discrete event systems (DES), such as manufacturing facilities or logistic systems, can be based on the exploration of the reachability tree of the Petri net (PN) of the developed model. Thanks to this technique it is possible to obtain a sequence of decisions that leads to an optimal behaviour of the system, according to one or several cost or benefit functions and a set of restrictions. It is supposed that the reader is familiarized with PNs and has a basic knowledge of its application; in [1, 8, 10] the basic concepts and properties about PNs are shown, [2, 3] present their application for modeling and simulation, and [4, 9] relate to the optimization of systems modeled with PNs.

Sometimes the original system is not completely defined, since it contains some undetermined parameters. In those cases several decisions should be taken in order to assign precise values to all these parameters, with the purpose of determining a resultant system capable to provide a maximal performance in the use of the invested resources during the start-up and normal operation. These decisions can be seen as design-decisions, different from the decisions taken in order to optimise the behaviour of a determined system, which could be seen as operation-decisions.

For example during the design process of a DES, some decisions that determine in a decisive way the final configuration of the system, can be: the location of warehouses of a logistic system or the number, the type and distribution of machines, manufacturing cells, transport devices and products storage of a manufacturing facility can be considered, etc.

Those decisions could lead to completely different systems, related to diverse models based on PN. Each one of these PN can be associated to a specific reachability tree which can be explored and provide particular solutions.

In certain cases the decisions in the design process can be reduced to a choice among a small number of options. In these situations optimization tasks can be developed for each one of the possible systems in order to perform later a comparison of the results.

Nevertheless the decision making process can be more complex in those cases where the range of possibilities is broad. In particular, to perform an optimization process for each one of the possible values of the parameters becomes an unaffordable task .

This paper describes and explores a general method to afford this kind of problems. The technique is based on the concept of macro-reachability tree, built up from the different reachability trees related to the different PN solutions of the considered decision making procedure.

The macro-reachability tree can be explored, for example, by means of artificial intelligence techniques or heuristics [5, 6], providing as a result not only the optimal decision for the design task but also the decision sequence which leads to an optimal manufacturing management when the system is in operation.

This macro-reachability tree is built from the set of all the possible models based on PN that constitute a valid solution for the considered system. This set of models can be a mere parametrized PN that depends on several values that should be determined [7,11]. On the contrary it could be built-up from a set of PN with different topologies, all of them suitable candidates to the definitive model of the real system to be implemented.

The search of a solution to an optimization problem by means of an exploration of the macro-reachability tree requires the systematic development of a series of steps, as to determine which characteristics of the real system are already determined and which ones should be chosen after a submission to an optimization process. Another important step is the definition of the model of the system itself, which depends on some parameters to be calculated and could consider a set of PN which includes the different alternatives to the original system. Another important steps are to define the function to optimize and the restrictions to be applied and to determine the exploration technique and to perform its implementation.

As it has already been mentioned, the most evident application of this method is the design of DES. This technique allows take decisions related, for example, to the type of resources to be used (machines, transport devices, product storages, etc) to their amount and to their location inside a manufacturing facility.

Nevertheless, this technique can also be applied during the operation period of a manufacturing system in order to choose an appropriate production strategy and production resources management. Another possible field of application could be the optimal planning of partial stops in the productive equipment to perform the preventive maintenance of the installation with the aim of perturbing the production yield to a minimum.

Finally, it can also be considered the application of this method to perform the decision making related to any enlargement or modification of a working manufacturing facility, process which could be assimilated to a layout redesign of the productive equipment.

The result provided from the application of the macro-reachability tree exploration is to obtain an optimal or merely a good solution, according to the chosen searching technique. This solution solves the decision making task related to the choice of a PN among a set of possibilities. On the other hand, this solution also provides values to the undetermined parameters of the original PN as well as the definition of a sequence of decisions that leads to optimize the production of the manufacturing facility in operation.

The aim of this article is to present a systematic treatment of the optimization process of certain problems related to models based on PN, by means of the exploration of a macro-reachability tree.

Moreover, another objective of the article is to show some application examples of this technique to manufacturing processes. In the mentioned examples the steps that have led to the final results, by means of the application of different searching methods like heuristics and artificial intelligence, are described.

In the section related to the conclusions, the computational performance obtained is to be presented, as well as the optimal solutions that have been found. On the other hand the design and production decisions that could be derived from the mentioned solutions are also commented. Some advices and difficulties found during the development of the technique implementation are also provided.

Finally the authors propose some open directions where the research in the field that is described in this article can be continued.

2 Technique Application

With the aim of illustrating the application of this general technique to a simple case, an example has been developed and it is described below.

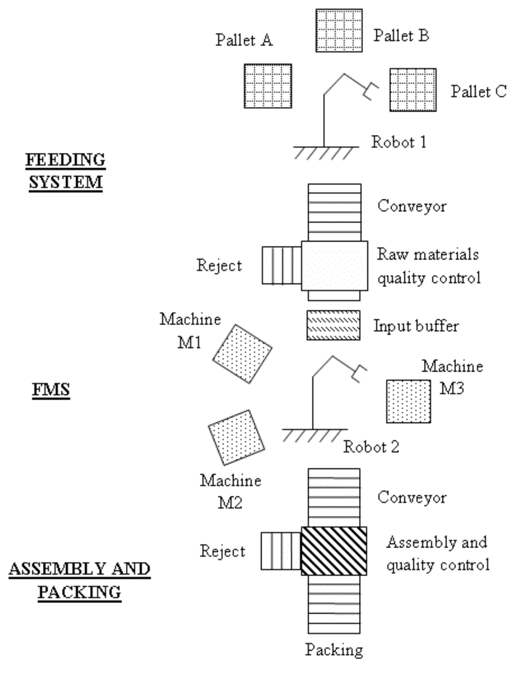

Fig.1. Layout of the first alternative for the system.

A manufacturing system in process of being designed is taken into consideration. Some of its parameters and its layout are undetermined. Therefore, it is an interesting objective to develop a tool capable to help in the task of taking decisions.

Usually some of those decisions, related to the design, have at this point already been taken based on previous economical reasons or any other motives.

The considered manufacturing system is organized in three stages: raw materials feeding system, flexible manufacturing system and assembling, and packing system. An approximated layout can be seen in *Fig 1*.

The facility feeding system handles three types of raw materials, which are provided in pallets. When a pallet is empty, a truck driven by an operative changes it for a full one. The warehouse has a limited number of pallets of each type.

A robot picks up the raw materials, one by one, and puts them onto a conveyor that drives them to a quality control. The result of the quality test can make some of the raw materials to be rejected. This fact introduces a random factor to the process.

The raw materials that have been considered suitable for the manufacture are led to the flexible manufacturing system. Between them a raw material buffer can be installed. Whether this buffer is needed or not is a fact that leads to a decision. The described technique in this chapter can help to take it.

The flexible manufacturing system is composed by three machines. Each one of them can operate on several raw materials and some of these raw materials should be processed in two machines. All the possibilities can be seen in *Fig. 2*.

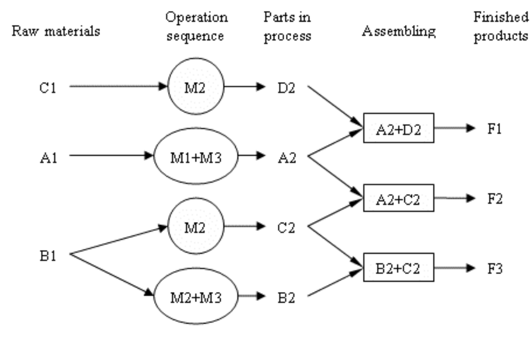

Fig.2. Raw materials, parts and products.

A robot can load and unload the machines from the feeding conveyor or from another machine and can put them on the output buffer or conveyor.

Another decision that can be important in order to obtain a high performance from the production line is the layout of the flexible manufacturing system. This means that the optimal disposition of the machines should be found to keep the handling time at its lowest value. The technique described in this chapter could also help to take this decision.

The processed parts are moved by the robot to an output system. Whether it should be an output buffer or not it is also a decision that should be taken.

Two different suppliers propose different solutions for the assembly and packing system. One of the possibilities is a flexible system composed by another robot, which feeds the assembling system, a final product quality control, and a conveyor to the packing system. Both alternatives are presented in *Fig 1* and *Fig 3*.

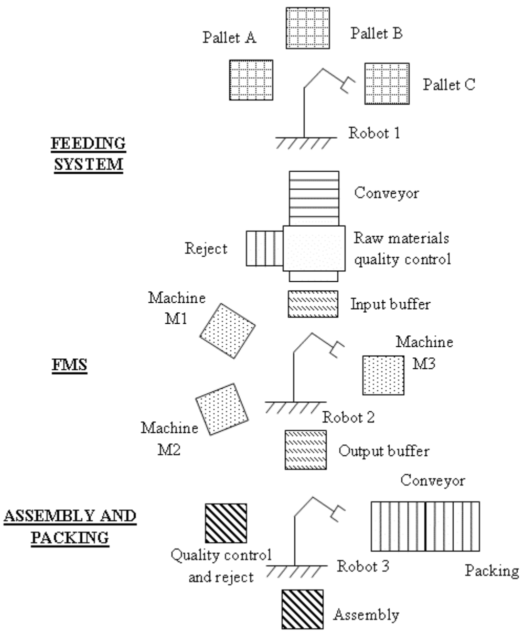

Fig.3. Layout of the second alternative for the system.

The other solution is a less flexible system, which consists of a conveyor that drives the parts to the assembly system and then the assembled products to the quality control. The third and final destination of the products on this conveyor belt is the packing system.

The technique described on this paper also can help in taking a decision which concerns to the choice of one of those systems for the final stage of this manufacturing facility.

In order to summarize the decisions to be taken in the design of the manufacturing system, the following ones can be selected:

- Capacity of the pallets where the raw materials are supplied.
- Number of robots in the manufacturing feeding system.
- Presence or not of a raw material input buffer for the flexible manufacturing stage.
- Size of this buffer in case that it was decided to be installed.
- Number of robots in the flexible manufacturing stage.
- Layout of the flexible manufacturing system. That is to say the relative positions of the different machines, conveyors and intermediate buffers.
- Layout and stations that will configure the assembling and packing stage.
- In case of this last stage is chosen as a range of stations loaded and unloaded by one or more robots, the number of them, the presence of an input buffer, and its capacity, are also decisions to be taken.

The way to afford the development of a tool to help in the process of taking the previous decisions begins with the choice of an appropriate modelling formalism. This formalism should allow build up a model of the system, which can show an accurate behaviour related to the real system. Coloured timed Petri nets have been chosen. They can handle with processes that are present on the normal operation of the facility that is being designed. These processes include competition for limited resources, cooperation between subsystems, parallel and concurrent operations, synchronization and conflicts, which, in some cases, should be solved with the appropriate production strategy.

The construction method that has been chosen to obtain the Petri net models of the system is called bottom-up method. That means that the system is divided into subsystems that are linked, in order to compose the total system, by means of common places or transitions.

This method is very appropriate to apply the macro-reachability tree exploration technique and the explanation can be founded bellow. Some of the decisions that should be taken during the design of an industrial facility lead to different systems that must be formally described by means of Petri nets with different topologies. In summary, each one of the solutions to that type of decisions is modelled by a different Petri net.

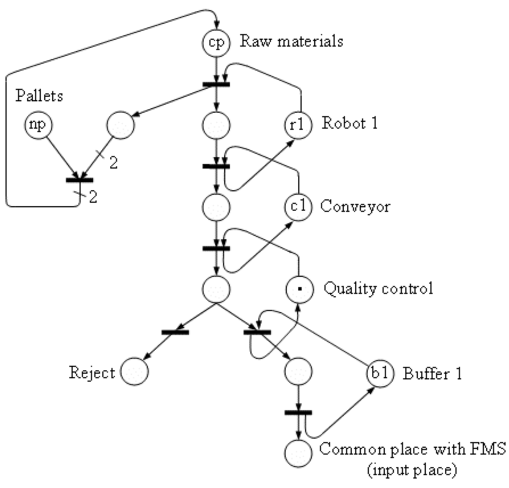

Fig. 4. Petri net of the feeding system.

That means that with the traditional reachability tree exploration it is necessary at least one optimisation process for each one of the solutions. What we propose in this paper is to build up a macro-reachability tree of the complete system including all the alternative topologies for the Petri net solutions of different decisions. In the example that we are considering now this fact is illustrated with the decision about the type of system that can be installed as assembling and packing system.

This problem has been afforded by means of the separate development of the PN for the different stages of the manufacturing facility. Four PN models have been developed. They have been linked by means of common places. Two of the models correspond to the feeding system and to the flexible manufacturing system. Both of them are detailed in *Fig4* and *Fig 5*.

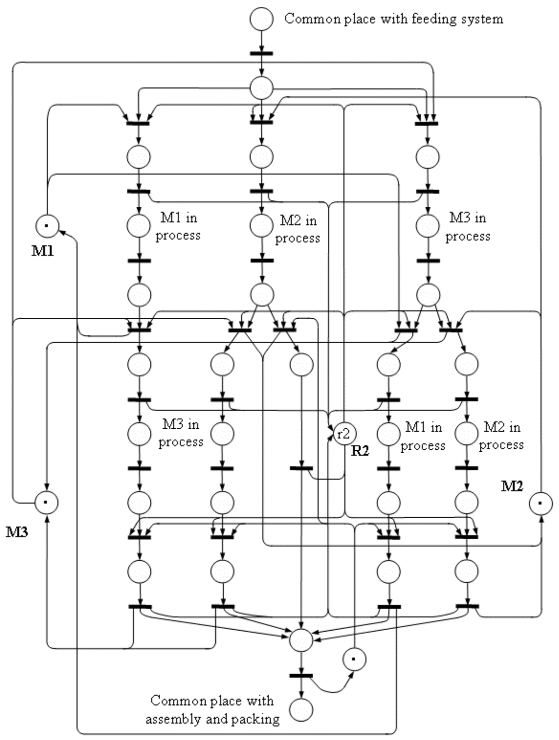

Fig. 5. Petri net of the flexible manufacturing system.

The other two ones constitute models of the alternative solutions for the last assembly and packing stage. In order to clarify the explanation, the two of them are presented in *Fig 6* and *Fig 7*.

As it can be seen a complete PN model with all the alternative topologies for the PN models has been built up. During the exploration of the complete reachability tree or macro-reachability tree the optimal solution is reached in both alternatives as all of them are properly integrated in the same PN structure. The process to extend this method to more alternatives has not any conceptual difficulty. The only work to do is to develop a PN model of the alternative subsystem and to integrate it to the macro structure of the complete system that already includes the other alternatives. As it can also be seen it is not necessary to develop a PN model for the complete system to consider the new alternative in the optimisation problem.

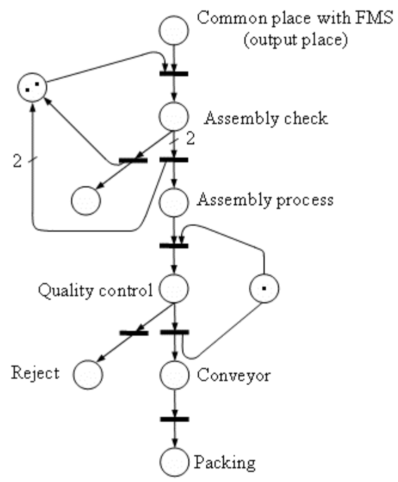

Fig. 6. Petri net of the first alternative for the assembling stage.

Due to the fact that the same manufacturing system processes several different raw materials and parts, a coloured PN has been chosen. A coloured PN allows to simplify and reduce the size of a Petri net when several types of parts are handled. A part of a certain type is codified as a token with a subsequent “colour”.

Therefore, in the same place of the PN, tokens of different colours can be founded. The behaviour of these tokens of different colours may be different when the Petri net evolves as it happens in a real system that can detect or remember the type of a part and act accordingly to this information.

In the example that has been developed, the three types of raw materials change into four types of semi-elaborated parts, and then again into three types of finished products. This fact has been taken into account with appropriate changes on the colours of the tokens in the places that model the actions that modify the part types. In order to reduce the computational effort of this information handling the dimensions of the data structure has been adapted to them. This fact constitutes another advantage of the modular treatment of the Petri net model as the data structure and other computing parameters can be adapted to the characteristics of one of these subsystems.

There are some parameters on the model of the system that should be adjusted properly for better accuracy on the behaviour of the PN according to the real system. For instance, the rate of raw materials and semi-elaborated parts that are rejected by the quality control equipment or the timing associated to some transitions.

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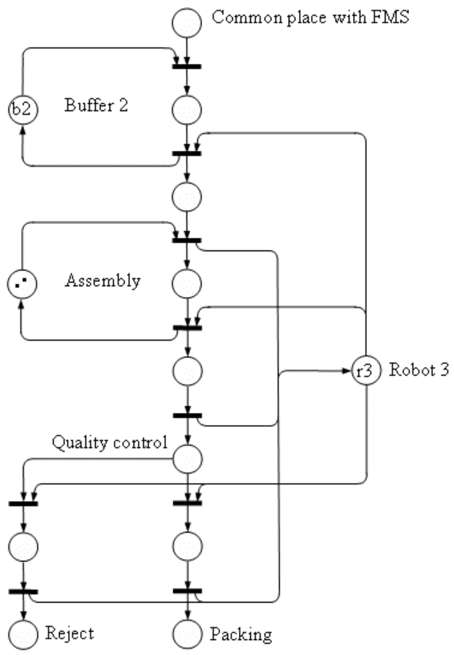


Fig. 7. Petri net of the second alternative for the assembling stage.

The rates of rejected parts introduce a random parameter in the behaviour of the system, which makes the same sequence of control decisions to provide different results. For this reason the optimized sequence of decisions cannot guarantee a literal repetition of good results. Nevertheless, some useful information for the control of the system can be deduced from the optimisation process:

- Number and rate of each type of finished parts that can be expected to be produced in the simulated manufacturing period.
- Number and rate of each type of raw materials and semi-finished parts that remain on the production system once the manufacturing period is finished.
- The effect that different parameters have on the optimal solution that has been founded.
- Sequence of decisions which in the simulated conditions have led to the obtained results and can therefore provide a good manufacturing strategy.

On the other hand, the mentioned timing, associated to the PN transitions, plays an important role in the optimisation process. This timing comes from the duration of the different operations that configure the manufacturing process: material handling, transport, operation of the machines, quality control, assembling, etc. Apart from the effect of this timing on the bottle-necks of the manufacturing process and on the facility behaviour in general, an optimisation of the timing allows take some decisions on the design of the manufacturing process.

Let us consider the layout of the different elements that configure the flexible manufacturing stage. One way to search the best location of the different machines, conveyors and buffers could be to search solutions in the complete set of possibilities provided by the different layouts. In fact, these possibilities are not related to different topologies of the Petri net model of the system. The structure of the Petri net will be the same in all these cases, but the timing associated to the transitions will be different. In the present example 6 possible layouts for the flexible manufacturing system have been considered. For all of them the time needed for each elementary operation has been estimated. All the layouts present differences in the timing of the material handling: loading and unloading of the machines, conveyors and buffer. The final solution of the search in the macro-reachability tree will choose one of those layouts which will be the option proposed by the optimisation tool to take a decision.

Another decision that has been suggested in this example is the possibility of installing an input buffer or an output buffer on the flexible manufacturing stage.

The first one, the input buffer, would be located at the end of a conveyor. When a raw material reaches the end of the conveyor, the movement of material along it will stop until a manipulator device removes this raw material from that position. The model of the Petri net can have a place associated to that last position of the real conveyor. When there is not any token on that place, the movement of the conveyor can continue and another token can be placed there and eventually substitute a formerly removed one. A real buffer at the end of the conveyor can be associated in the Petri net model to this last place. An associated place will contain initially a number of tokens that equals the number of vacancies in the buffer. Therefore, the different situations related to a FMS without input buffer or a FMS with output buffer of a certain capacity can be modelled by means of Petri nets with the same structure. The only difference between them will be the initial marking of the associated place. When the amount of initial tokens, which represent the vacancies in the buffer, is one, there is no buffer but a place at the end of a conveyor. When this initial marking contains n tokens, the capacity of the buffer is n. As a conclusion of the previous commentaries we can consider that providing help to take a decision according to the presence and capacity of this buffer is equivalent to optimise the initial marking of the associated place of the Petri net which contains as many tokens as vacancies in the buffer.

Another cases of this example in which the optimal solution has been associated to an initial marking optimisation are the capacity of the pallets of raw materials and the number of robots for a certain task (feeding with raw materials the FMS, loading and unloading the machines, etc.).

It is important to consider that in order to reduce the search space of the problem some restrictions should be impose to the possible values which can be related to these initial markings. Those values should be limited by an upper and a lower boundaries.

The last optimisation considered is the one associated to a sequence of manufacturing decisions that can lead to an optimal yield. This classical optimisation problem is afforded in this example with a search in the macro-reachability tree of the models of the system. Each time an effective conflict is produced and there is not enough information in the model to solve it, a decision must be taken.

In this example usual conflicts can be found in the following situations:

- The robot in the line feeding stage is in position to pick up a raw material. In this case, if there are available raw materials of all the types, the control system must decide which one should be loaded on the conveyor.
- The robot in the flexible manufacturing system handles a raw material and all the machines suitable for processing this raw material are free. In this case the control must decide on which machine the robot should load the raw material.
- The machine M2 has finished processing a B1 type raw material. There are two possibilities for the following step: the control should decide if the piece is driven to the assembling station or, on the contrary it is loaded on machine M3.
- The last effective conflict that can appear in this example is less obvious to predict. In the FMS there is a competition for the limited resources: the robot and the machines. In certain situations the control should determine which piece among the available ones should the robot pick up.

The first step of an optimisation problem, as it has been described before, is to build up the alternative models of the system, including finding the most realistic values of certain model parameters.

The second step is to define in a precise way the different types of optimisation problems that should be afforded.

The third step could be to obtain a benefit function able to characterize a certain solution of the optimisation problem with a real number. This benefit function allows compare two or more solutions and determine which one is the best. As it can be guessed the importance of tuning properly the benefit function is a capital matter for the success of the optimisation process: different coefficients and terms in the benefit function can lead to different recommended solutions to the design decisions that should be taken.

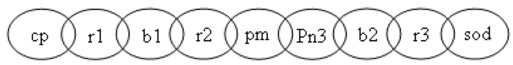
In the example considered in this paper a benefit function has been chosen according to the particularities of the system. In this benefit function economical factors appear as well as others whose purpose is to penalize or favour certain decisions according to other non-economical drawbacks and advantages. This other factors are difficult to evaluate and to convert into a coefficient but it is worth the effort to take them into account.

The benefit function, to be optimised, should favour the production and penalize the non profitable investments. The bad materials rejected in the quality controls will penalize a certain solution. Also those parts of the manufacturing system that are rejected because of bad manufacturing decisions they may penalize despite they might be re-used. Finally all the raw materials and parts that at the end of the production period are present on the production line but not in the packing station as finished parts will also penalize.

As it has been seen there are some coefficients in the benefit function that are constant and multiply the different number of parts and products. Nevertheless, there are other terms that are independent to the yield. They are fixed costs like the redemption amounts of the technology investments, which should be distributed along the profitable period of operation of an industrial facility. These terms are composed by two factors: a constant coefficient and the period of manufacturing time considered in the solution of the optimisation problem. If this time does not appear on this term, as long as the simulation time is increased the “fixed costs” would decrease in the same proportion.

The forth step of an optimisation problem based on the search in the macro-reachability tree of a certain set of Petri nets would be to chose and adjust a technique to solve it. There are a large amount of methods available, which have been used to conventional explorations of reachability trees. The algorithm that has been chosen in this example is an evolutionary one.

It is not the purpose of this paper to enter in detail in the description of a genetic algorithm. Only some practical aspects will be commented in order to deal with a macro-reachability tree in general and to this example in particular.



Abrev.	Parameter to be optimised	Boundaries
cp	Pallets capacity	[1,20]
r1	Number of feeding robots	[1,3]
b1	Capacity of FMS input buffer	[1,10]
r2	Number of FMS robots	[1,3]
pm	FMS layout	[1,6]
Pn3	Assembly and packing layout	[1,2]
b2	Capacity of FMS output buffer	[1,10]
r3	Number of assembly robots	[1,3]
sod	Sequence of manufacturing decisions	[1,3]

Fig. 8. Structure of a chromosome in the genetic algorithm.

The purpose of a genetic algorithm is to build populations of solutions to the problem in order to find a good one among them (the optimal one, if possible). Some random parameters that should be adjusted determine the rate of renewal of the population in each generation of solutions, and the way the solutions are mixed to create new ones. In a general case, a solution is called a chromosome and contains all the important information to define the parameters that have been chosen to be optimised.

In the example described in this paper the chromosome contains a sequence of data including all the parameters to be optimised, for instance the capacity of the buffers, the number of robots, the type of assembling and packing which has been chosen and a certain layout for the FMS. The complete structure of this chromosome is detailed in the *Fig.8*.

The operation of the evolutionary algorithm needs some parameters. Apart from the adjustable parameters of the technique itself it is necessary to be defined the number of generations to be explored and the manufacturing time that should be simulated with each solution.

In the same way than other more conventional state space searches, the macro-reachability tree search, by means of non-deterministic strategies (heuristics or artificial intelligence), requires the adjustment of the algorithm parameters to the particular search. This process should be carefully afforded in order to obtain the best solutions.

When a good solution is obtained it is possible to use the information that it provides to help in the process of taking a decision. This stage starts the fifth and last step of the optimisation process: the interpretation of the numeric values and their translation to specific suggestions that can be considered in some decisions of a DES design. If the previous process of posing the diverse optimisation tasks has been rigorous and systematic (and the macro-reachability tree concept helps in this way), this last step should not present any important difficulty.

3 Conclusions and research ways

The design of a discrete event system to be applied, for instance, as a manufacturing facility or a chain supply, is a complex task that involves a large number of factors that must be considered. The help that an optimisation tool can provide to the process of taking decisions is not negligible. Nevertheless, it is not trivial the way to afford a complete optimisation of a large amount of diverse parameters of the system. As it has been described in this paper there are several types of undetermined aspects that can appear in a design process and lead to the obligation of taking a decision. There are several options to convert these uncertainties into PN optimisations like marking, timing or topology optimisation. Once the optimisation problem is posed, the search of an optimal solution among the state space of the model of the system is a task that can be achieved by means of several techniques. The heuristic or artificial intelligence algorithms, which have been developed to guide the search and try to find a good solution, can be applied to the reduced state space of the different alternative topologies. In this paper an integrated point of view has been proposed, where an amount of optimisation problems can be joined and solved at a once. In order to afford that challenge it is necessary to group all the possible state spaces into one. The search of an optimal solution is then modified. From individual reachability trees associated to the different Petri nets topologies the search is extended to a macro-reachability tree which involves all the Petri net alternatives.

The union of different state spaces must be carefully afforded. The best option is a modular Petri net model design, which can be developed by means of a bottom-up process. The different models can be then joined by means of common places or transitions. Following such a systematic Petri net model treatment the possibility of making a mistake or inaccuracy in the process is minimized.

Once the optimisation tasks have been reduced to one, the advantage in the treatment of a unique problem is clear: at a once all the optimised parameters can be obtained, all the effort can be focussed to only one problem and it is the searching method the one that compares and chooses one of the topologies as the optimal one. According to this idea it is not necessary to take decisions according to subjective comparisons between different optimal solutions associated to different Petri net topologies. This systematic treatment of the optimisation problem presents another advantage. It leads to an objective strategy of alternative topologies comparison. The obtaining of this objective strategy is a consequence of the development of the algorithm to unite all the reachability tree searches into one. As a vital part of this algorithm the benefit function to be optimised should contain addends related to the diverse Petri net topologies on a common base to allow the comparison.

On the other hand, it may happen that a rigorous posing of a macro-reachability tree search could be more difficult than to pose other individual simpler ones. Nevertheless the solution of the first one may allow rule out a lot of inefficient investments in a manufacturing or logistic system design.

We continue developing this research line in other to improve the behaviour of some interesting real applications we are working in, and to apply the results in some benchmarks in order to assure its profitability.

Some of the situations that can be explored are related, for instance, to the different manufacturing strategies that lead to diverse Petri net topologies. It is an important issue to compare the results obtained in a reasonable amount of systems by means of the different strategies of individual alternative reachability trees and macro-reachability trees exploration. One of the main purposes of that comparison would be to obtain conclusions related to the quality of the solutions.

The following strategy will also be analyzed from diverse applications of the technique. When we consider an undetermined system, that is to say a system in process of being designed, for which a certain number of Petri net models can be associated to its different alternative topologies, we could find as a reasonable strategy to begin with a search in the macro-reachability tree in order to choose a solution. The next step could be to refine the solution. If there is a marking optimisation problem included in the task, this refinement of the solution could be managed by means to a specific search in the reachability tree of the chosen Petri net topology.

Finally, it is important to evaluate the added effort and the advantages that arise from an integrated and systematic treatment of a macro-reachability tree exploration, and to extend the conclusions to a classification of optimisation problems. More general results are expected from the macro-reachability exploration in order to provide a global technique that simplifies the application of the optimisation methods to complex design discrete even systems design.

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