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54th CIRP Conference on Manufacturing Systems

Solving Facility Layout Problem with safety consideration of Reconfigurable Manufacturing and Assembly Systems

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Abstract

Reconfigurable Manufacturing Systems (RMS) are designed to cope with mass customization problem. Reconfigurable Assembly Systems (RAS) are a variant of this RMS concept in the assembly field. One of the most crucial issues in designing the RAS is the layout problem with human safety considerations. This paper's main motivation is to propose a methodology to determine the most efficient and safe arrangement of facilities in a workshop. The objective is twofold: (i) to minimize the Material Handling Cost and (ii) to ensure human safety by applying "safety bubble". An implementation of the approach and an illustrative case study are presented.

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1. Introduction

Nowadays, the manufacturing environment testifies fluctuations in production demand and a fast introduction of new products that leads to ferocious global competition. By the end of the 20th century, a new concept of production systems called "Reconfigurable Manufacturing Systems" (RMS) was introduced to deal with unpredictable market changes. RMS were introduced firstly by [1] to enable industries to be flexible, agile and responsive in unstable conditions. Such systems' overall structure is composed of a set of basic units (e.g., robotized unit, conveying unit...) that can be easily added, removed, modified or configured to meet dynamic market demands or to cope with external changes (e.g., new product introduction, machine breakdown) [2]. The layout design is a crucial step to design RMS. The importance arises because the layout decides how materials, products, manufacturing operations, and processes circulate through a given area. Recently, managing the positioning of facilities within an RMS layout is a current subject that has

attracted researchers [3]. Many research efforts have been mainly conducted in RMS problem [4].

Nevertheless, facility layout design for RMS is a significant gap that has not been regarded so far. Facility Layout Problem (FLP) aims to determine the most efficient physical organization of n facilities (or cells) in a given area. In the context of RMS, the layout must match the current market requirements, i.e., it needs to be reconfigured frequently to maintain high performances in terms of productivity of the manufacturing system [5]. The layout must deal also with human operator safety issues. Moreover, very few research works explore human safety issues when resolving FLP in RMS [6]. This safety issue must mandatory be considered when the RMS contains dangerous equipment such as classical industrial robots.

To address these issues, two complementary contributions are proposed: (i) to solve the facility layout problem (i.e., how the cells of the RMS will be arranged or rearranged in a given area) using Genetic Algorithm (GA) and A* search algorithm; and (ii) to ensure human/operator safety using the "safety bubble" concept.

The rest of the paper is structured as follows. Section 2 focuses on relevant literature dealing with the two issues (i.e., facility layout and safety problems in designing RMS). Section 3 defines the adopted methodology (off-line and on-line phases) to solve FLP with human safety considerations. Section 4 describes the experimentation carried out to validate this research. Finally, Section 5 summarizes the paper and presents directions for future works.

2. RELATED WORKS

Reconfigurable manufacturing systems are adjustable structures (from both hardware and software points of view) [7] that can be modified quickly and easily to deal with the required adaptability [8]. Hereupon, many research efforts have been carried out in the field of RMS. Among them, some survey papers are produced to analyze the relevant research approaches [2, 9]. According to [10], the RMS optimization problems are gathered into four categories: (i) process planning, (ii) layout design, (iii) reconfigurability, (iv) planning and scheduling. If many research efforts have been carried out in the field of RMS, few research works have dealt with the facility layout problem and the inherent safety issues.

2.1. Works on RMS layout issues

In the RMS literature, there are only a few studies on the layout design problem [2], although the FLP is a critical key issue in RMS. A new configuration must be proposed by switching from one product family to another [11]. [12] provide a model for the layout optimization of manufacturing cells and an allocation optimization of transport robots in reconfigurable manufacturing systems using particle swarm optimization algorithm. [13] adapted an electromagnetism-like mechanism for the layout design of reconfigurable manufacturing systems. The main objective is to minimize material handling and reconfiguration costs. The authors considered AGVs, which were used to transport any product from one workstation to another. From another perspective, [14] studied machine layout design problem under product family evolution in a reconfigurable manufacturing environment.

The FLP methods and techniques attempt to resolve the problem of facilities (e.g., cells, machines, departments) placement within a given location. RMS have an impact on layout and material handling systems. RMS undergoes frequent configurations to meet different production requirements and serve the new systems' requirements. The main objective of the FLP focuses on minimizing the Material Handling Cost (MHC) because, according to [15], approximately 20–50% of the total operating expenses in manufacturing environments are attributed to the MHC. MHC is associated with the material flow and the travelled distance between machines. Most of the existing research works use Euclidean or rectilinear distances without obstacle to calculate the travelled distance between equipment. Very few works [16, 17] take into account, for example, the

presence of obstacles in the workshop. The facility layout resolution depends on workshop and facilities size and shape, number of floor (single or multi-floor layout), static or dynamic layout consideration with or without obstacles (restricted or unrestricted) [18, 19, and 20].

Since the FLP belongs to the NP-hard problem, several FLP resolution approaches, including exact and approximated methods, have been developed to find (sub-) optimal solutions. Recent research has focused on meta-heuristics methods such as Particle Swarm Optimization [21, 22], Tabu search [23], and Genetic Algorithm [24, 25]. These Meta-heuristics are used to obtain efficiently good layouts for large-scale problems. The Genetic algorithms have proven to be appropriate in designing manufacturing systems and their facilities.

2.2. Works on safety issues

Besides the lack of layout design problem researches, very few studies explore the inherent safety problems in RMS [26]. Safety is a top priority for everyone working in manufacturing, mainly when dangerous equipment are used. Fatigue and carelessness further increase the risk and can lead to severe injuries in the absence of the right protective equipment and procedures. For all these reasons, there is an essential need for original approaches to ensure human safety in such a dangerous environment.

Several traditional safety approaches with successive steps (i.e., risk analysis, risk assessment, and risk reduction) have been developed in the literature for various types of manufacturing systems (e.g., dedicated manufacturing lines, flexible manufacturing). Nevertheless, these approaches show various weaknesses and fail to take into account the versatility of RMS [6]. In addition, these approaches must be applied for each new configuration of the RMS. This requires tremendous time-consuming work by experts (i.e., safety managers), and then only a few configurations can be studied and certified as "safe" [6]. The safety manager must analyze each new configuration taking into consideration the standards (e.g., ISO 10218-1 [27], ISO12100 [28], ISO 13855 [29]), directives (e.g., 2006/42/EC [30]), and technical knowledge of the system. Traditional safety approaches consider fixed barriers as safeguards for dangerous equipment [31]. However, such procedures cannot be considered for RMS because it will take a long time for reconfiguration.

3. PROPOSED METHODOLOGY

Our research work aims to fill the lack of research work on both facility layout problem and human safety in RMS. Firstly, the Genetic Algorithm integrated with A* search algorithm are used to find the best facility layout [16]. More precisely, the Genetic Algorithm is used to generate various configurations candidates to minimize the total transportation cost. A* search is used to determine the shortest path between two machines. Afterwards, we propose the safety bubble approach to assist safety managers in implementing the safety

devices, especially safety laser scanners (SLS), and therefore ensure human safety.

The methodology concerns RMS but has been developed for Reconfigurable Assembly Systems (RAS). RAS are RMS dedicated to assembly tasks [32]. A RAS is composed of one or several cells. Each cell consists of a set of basic connected units (e.g., robotized unit, conveying unit...) [33]. In addition, for example, a fleet of mobile robots can be used for material handling to transport products between different cells. As illustrated in Fig.1, we consider that each RAS cell is based on three types of units:

1. Robotized units (RU) which are composed of industrial robots and on which operators occasionally intervene (maintenance, for example).
2. Conveying units (CU) used to transport products between various units.
3. Manual units (MU) where operators work continuously. Other units, where operators frequently intervene, such as inspection/storage units, can be considered as MU.

The studied workshop is a real installation at Hauts-de-France Polytechnic University.

The proposed methodology to design and implement the RAS operates in two phases: off-line and on-line.

3.1. The off-line phase

This phase considers three main steps:

RAS cell design

This first step is dedicated to the design of each cell considered alone. The output is a geometric representation of each cell with the locations of the different basic units. This step is not detailed in this paper.

RAS layout design

The FLP consists in positioning a set of n cells in a plane of fixed length (L) and width (W). As mentioned in Figure 1, cells have different sizes and irregular shapes.

Each cell is characterized by its length (l_i) and width (w_i) and the coordinates of its centroid (x_i, y_i). The workshop contains obstacles such as storage areas, walls or stairs. The main constraints for this problem are: (1) Bounding constraints to ensure that all cells are located within the given perimeters of the workshop, (2) cells non-overlapping constraints, and (3) cells and obstacles non-overlapping. The main objective function is to minimize the Material Handling Cost (MHC) which is associated with the distance travelled

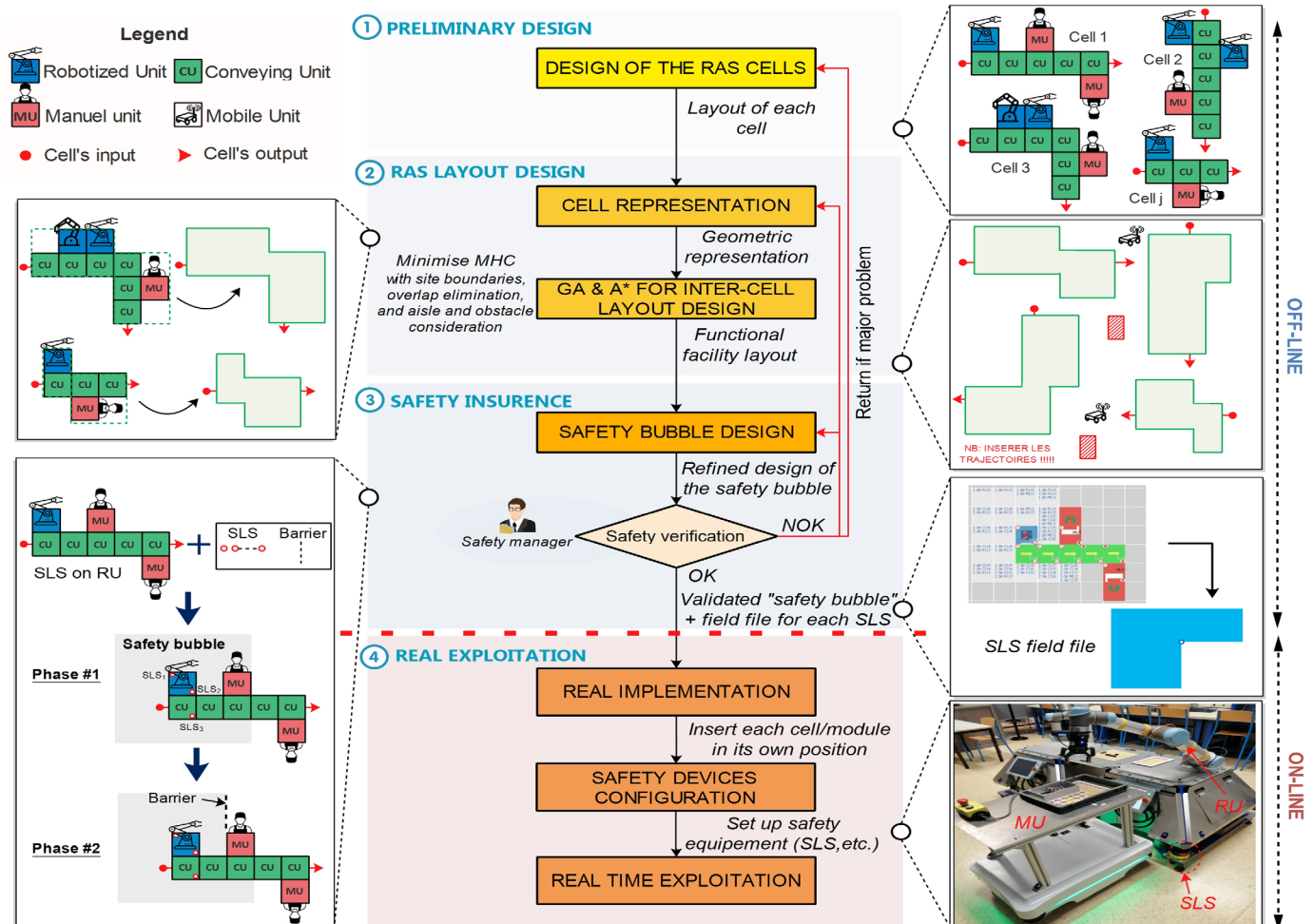


Fig. 1. The proposed methodology

by the material flow between cells. This distance is calculated by using A* search algorithm because the A* algorithm calculates the actual distance travelled, taking into account the presence of obstacles. A* algorithm is the standard graph algorithm for the shortest path problem taking into account obstacles. The generation of the different Layouts is done using the genetic Algorithm, which operates with a population of chromosomes. Each chromosome represents a possible solution (i.e., a configuration of the workshop) and is characterized by its fitness value. The fitness value of an individual (solution) represents its quality according to the MHC. Each solution represents the coordinates (xi, yi) of the centroid of each cell in the planar site. The length of the chromosome corresponds to the number of cells. The initial population is randomly generated; each individual representing a workshop configuration. The population of individuals (i.e., configurations) are evolved iteratively looking for improving the quality (or MHC) of individuals or configurations. The evolution process is made of four main steps: parents' selection, crossover, mutation, and offspring selection. The main goal of this process is to improve the quality of solutions, and it is repeated until a stopping criterion is reached (Maximum number of iterations in our case). For a detailed overview of this approach (Genetic algorithm integrated with A* algorithm), readers are invited to refer to [16].

At the end of this step, a precise layout of the RAS is provided with the locations of the different cells. The next third step is dedicated to the safety study of the previous generated layout.

Safety design and verification

The "safety bubble" approach is proposed to assist safety managers in implementing the safety devices (e.g., SLS, barriers) and therefore ensure human/operator safety. This approach is based on the detection of human intrusions in the areas of robotic units and the construction of a "safety bubble" around the robots according to the methodology explained hereafter:

"Safety bubble" design: a tool, based on NetLogo [33], is used to assist the building of the "safety bubble". This tool considers two phases:

- (i) An algorithm determines SLS devices' location and, therefore, ensure robotized units safeguarding.
- (ii) If a MU is located closer to the RU and the required safety distance is not guaranteed, some barriers (which must be installed) are automatically generated between MU and RU. For instance, in Fig. 1, a barrier is installed between RU1 and MU1 to directly prevent operators from penetrating the robotized area.

Note: we assume that only RU are equipped with SLS devices placed on two opposite corners. Additional SLS devices can be implemented on the other units if necessary (the number/location of these SLS are given according to the developed algorithms).

"Safety verification": an algorithm is developed to assist the safety manager and verifies all the safety standards,

namely the safety distances around each RU. If the verification result is not satisfactory, a new configuration of the safety bubble must be generated, or at worst (e.g., major problem unsolved by the safety bubble), a new RAS layout design must be generated.

Once the safety verification of cells is done, the on-line phase (i.e., real exploitation) can begin.

3.2. The on-line phase

Three steps are considered:

Real Implementation

During this first step, the considered cells and units are placed in their respective locations (given by the RAS layout). The units are coupled physically to allow the transfer of products and if needed digitally to share data through a wired safety LAN.

Safety devices configuration

All the SLS are configured as specified by the field files generated off-line.

Real-time exploitation

In this phase, the RAS is fully operational. The safety devices are operational and share data to detect any human intrusion into the robotized areas.

In the next section, an example is provided to illustrate the proposed methodology.

4. NUMERICAL ILLUSTRATION

The previous methodology is applied on a RAS prototype in LAMIH. We assume that the latter contains 5 cells within a workshop (L=25 units and W=15 units). The dimensions of the cells are provided in Table 1. The input data corresponding to the obstacles are presented in Table 2. The quantity of the products flow between cells is presented in Table 3. The software tools used to solve facility layout problem and safety issues are respectively Matlab and Netlogo.

Table 1. Dimensions of cells

Dimensions	1	2	3	4	5
l_i	5	3	5	3	3
w_i	4	5	6	3	3

Table2. Input data of obstacles

Coordinates (x,y)	Length	Width
(9,13)	2	2
(12,4)	4	2

Table 3. Quantity of material between two cells

Facilities	1	2	3	4	5
	0	0	25	10	10
		0	35	12	12
			0	20	15
				0	0
					0

Discussion of the obtained results

The resolution of the off-line phase of the problem was done in a sequential way. As shown in Figure 2 and Figure 3, the authors started with the resolution of the Facility Layout problem in order to minimize unnecessary travel and then they are interested in the security aspect. The resolution time of FLP is about 30 min and few seconds are necessary for the safety analysis. The suggested approach proves its ability to explore a wide range of solutions by considering realistic distances between cells and human operator safety issues.

In Fig.2, the yellow blocks represent the cells. The pink rectangles represent the obstacles in the workshop. The empty spheres represent the inputs and the full spheres represent the outputs.

As exhibited in Fig. 2, all cells are placed within the limits of the workshop without overlapping, satisfying a set of constraints. The proposed approach FLP also determines the shortest path between cells represented by colored lines using A* search algorithm.

Once the best configuration is obtained, the approach determines the shortest path traveled between two cells using A* search algorithm (see in Fig. 2 the configurations with an extract of the routes to obtain a clearer visibility).

As explained in the previous section 2, very few studies have explore the safety problems in RMS. Compared with traditional approaches, considering fixed barriers as safeguards for dangerous equipment, our proposal is able to deal with the reconfigurable characteristic of a RMS. Traditional safety approaches (i.e. risk analysis, risk assessment, and risk reduction) must be implemented for each new configuration of the RAS. This requires tedious, time-consuming work by experts and then only a few configurations can be studied. In our proposal, the safety manager is assisted by a software tool to quickly build a safety bubble with programmable safety devices (i.e., SLS).

As illustrated in Fig. 3, the safety analysis for the cell #4 allows to:

1. Determine the adequate locations of the SLS to secure the RU
2. Add a barrier between the RU and the first MU

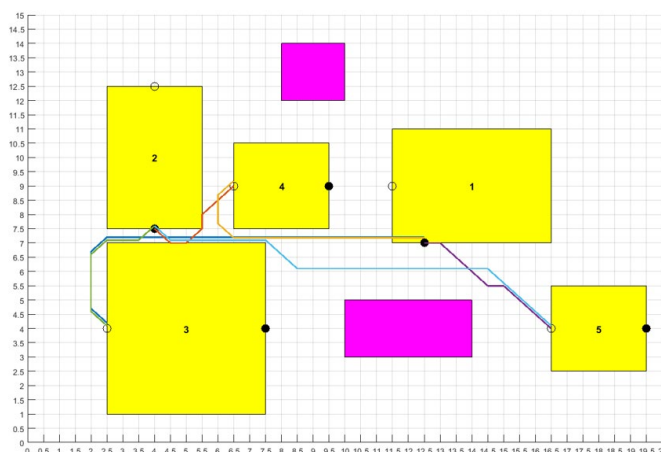


Fig.2. Best configuration with product flow obtained by <GA,A*>

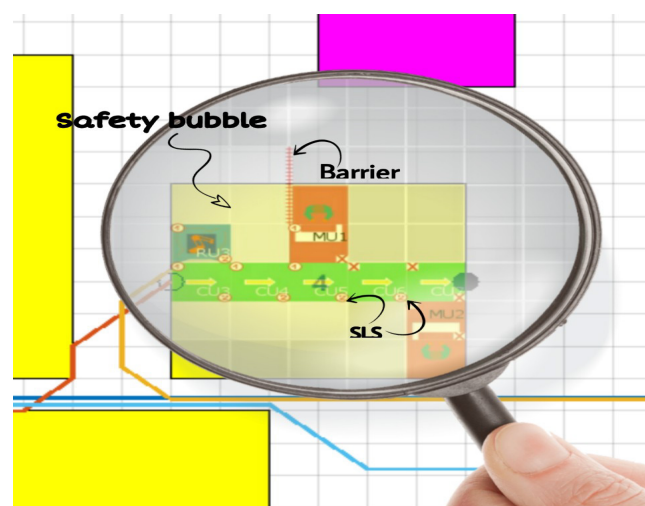


Fig. 3. Safety design and verification-Netlogo platform

5. CONCLUSIONS AND PERSPECTIVES

The main contribution of the present work is to firstly arrange cells in a given area in order to minimize Material Handling Cost, and secondly take into account safety issues in RMS context. To solve the layout problem, Genetic Algorithm was used to generate the different configurations and A* search algorithm was used to determine the shortest path between cells. To address safety issues, this study has proposed the “safety bubble” concept to face the inadequacy of traditional approaches dealing with safety issues in RMS. The effectiveness and the practicability of the proposed approach have been validated for the “off-line” phase. For future studies, authors aim to verify the practical feasibility of the approach for the “On-line” phase on a real RAS demonstrator. Afterwards, authors will be interested in intra-cell layout design. In another perspective, the authors seek to solve the problem in a simultaneous way in order to include the concept of safety bubbles in the model used for FLP.

Moreover, the authors aim to extend the proposed model towards multi-objective facility layout problem taking into account other constraints (orientation of cells, shape of cells, number of floors, etc...). Concerning the safety issues, future works concern the design of cooperative safety approaches using fusion of information, able to take into account the cohabitation of mobile robots and humans in the vicinity of the robotized units. Finally, our approach can be extended and used as a good basis for the development of an advanced support tool to help designers in finding the most effective and safe arrangement.

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