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Layout Design and Reconfiguration in a Collaborative Manufacturing Network

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Abstract. This study explores strategic agility of an automotive corporate group and its influence on facility layouts and operational performance. Strategic agility is viewed here as a firm's strategic intent to achieve agile operations through collaboratively deploying the layouts of a set of facilities, driven by a management focus on improving its responsiveness and adaptability to customers' requirements. Our "collaborative multi-facility layout problem" involves the physical organization of departments between and inside several facilities geographically dispersed, that collaborate in manufacturing a complex product in a given time window. The model proposed in this work allows us to analyse the benefits of new horizontal collaboration forms with respect to several objectives, namely costs (material handling inside and between facilities, re-layout) and adjacency between departments. A case study of a first tier supplier in the automotive industry shows the applicability potential of the approach to real-life problems. The results show that horizontal collaboration among the facilities can positively influence the performance of the corporate group as a whole, and that of each firm individually.

Keywords: Agile operations; multi-facility layout problems; multi-objective optimization; reconfigurable layouts; collaboration.

1 Introduction

In a more and more competitive world, companies easily recognize they need to permanently develop new and more sophisticated strategies, in order to maintain and increase their performance. The reconfiguration and continuous optimization of resources and production processes can be a way to reduce costs and increase their opportunities and profit [1]. The integration in Collaborative Networks (CN) can also be an important step to make organizations more effective and agile as part of broader manufacturing systems, and this may be specially important for SMEs, due to their reduced dimensions and high vulnerability. In this context, one of the current big challenges for industry is clearly the permanent need for rapid reconfiguration of

manufacturing enterprises, in response to changing requirements and opportunities [2]. In practice, the configuration of facility layouts comprises the physical organization (of departments, machines, workstations, storage spaces, etc) inside a plant, thus facilitating production and material handling, and allowing flexible and efficient operations [3].

In a more ambitious way, and as proposed in this work, the combination of design and reconfiguration of layouts for collaborative networks of facilities, can in fact help companies to be more flexible and competitive. Therefore, the main research question of this work can be stated as follows: “in a dynamic network of factories, what impact can sharing departments among facilities have on the flexibility level of this network and on each factory individually?”

To answer this question, we propose a mathematical model (a quadratic integer program) to be used in assigning projects of complex products to networks of facilities and in designing the layout of each specific facility. These networks can be viewed as a kind of Virtual Enterprises (VE). In fact, in our particular case, the facilities are part of a corporate group, and even if they are not fully independent from each other, they own all the other main characteristics of a VE.

The next section of the paper presents a brief state of the art on facility layout and network collaboration, as a way to position the contributions of the proposed model and to highlight its innovation. In the following sections the problem under study is described, followed by a presentation of the model. Then preliminary computational results are presented. The paper ends with some conclusions on the presented approach and with topics for future research.

2 Literature Review

The concept of *Collaborative Network (CN)* is currently widely disseminated and recognized as an important instrument for the competitiveness and survival of organizations, specially in periods of turbulent socio-economic changes [2]. A CN is a network of a variety of entities (e.g. organizations and people), largely autonomous, geographically distributed, and heterogeneous in terms of operating environment, culture, social capital and goals, but that collaborate to better achieve common or compatible goals, thus jointly generating value, with interactions supported by computer networks [2]. In CNs, *Virtual Organizations (VOs)* are an important class, characterized in four dimensions as follows: space (physically dispersed), time (asynchronous), mode of interaction (electronic networks) and individual diversity (different) [4]. A particular case of VO is the *Virtual Enterprises (VE)*, representing a temporary alliance of enterprises that come together to share skills or core competences and resources in order to better respond to business opportunities, and whose cooperation is supported by computer networks [2].

A rapid formation of VOs, when needed, and their adjustments to the specific requirements of a given emerging opportunity is of great importance and is frequently viewed as a requirement for agility, and used as a survival mechanism in face of market/society turbulence [1].

Strategic agility is viewed in the literature from quite different managerial perspectives (e.g., operations, information systems, marketing, human resources) [5]. For example [6] define agility as “a successful exploration of competitive bases (speed, flexibility, innovation proactivity, quality and profitability) through the integration of reconfigurable resources and knowledge management to provide customer driven products and services in a fast changing market environment”. Recently, [7] consider that agility is the project team’s ability to quickly change the project plan as a response to customer or stakeholders needs, market or technology demands in order to achieve better project and product performance in an innovative and dynamic project environment.

In fact, given today’s frequency of changes in business environments, it is more and more important for companies to be flexible as a way to respond quickly and dynamically to those changes. This response capability should also exist at a higher, corporate level, combining a plant-level and a network-level analysis that aims at understanding the continuous interaction between individual plants and their constituent networks [8].

In the context of this work, we aim at applying these concepts to extended facility layout problems (FLP), that in fact encompass various types of situations, such as the allocation of departments inside facilities [9] or machines inside departments [10]. This area has been studied from several different points of view, considering: the type of layout configuration (single row [11], multi-rows [12], multi-floor [13], cellular [12], ...); the type of problem (department/machine allocation, product flows [10], routing [14], ...); the objectives (single [12] or multiple [15], minimizing costs [12] or distances [16], or maximizing adjacencies [17], profits [18], ...) and constraints (overlap, budget [18], areas [19], ...); the nature of the problem (static [10] or dynamic [17]) and solved by a large variety and combination of resolution approaches (exact methods [20], heuristics [21], ...).

Due to the large impact that the layout has in a manufacturing company, recent studies tend to add more and more features to the basic, traditional problems. This is e.g. the case of [10] that integrates the layout design (by the location of unequal-area machines with duplicates) and the product flows assignment problem (by assigning products to machines according to the product process route). The work by [17] is another example, they propose a dynamic allocation of departments, considering multiple objectives (minimize total material handling costs (MHC) and re-layout costs, and maximize adjacencies), solving the problem with classical optimization methods and with population-based metaheuristics.

Although the FLP has been extensively studied (for some surveys see for example [22], [23], [11]), the majority of works deal with the design and reconfiguration of layouts at a single facility. The model proposed in this work intends to cover this gap, by simultaneously designing the layout of a group of facilities, and performing the allocation of products considering the whole network. Therefore, an innovation of our research comes from considering capacities in the transport of materials between facilities, and from allowing the possibility of performing changes along time.

Moreover, the model allows the addition or removal of departments and facilities at different periods, thus providing a higher level of flexibility.

3 Problem Description

The automotive industry works with “projects” that are associated with specific models of a car. A project comprises several parts that are themselves composed by a group of materials or components (see Fig. 1).

The mathematical model proposed in this work considers a set of geographically separated facilities that can produce and store the same type of products and components. Each facility has more or less the same department structure, with the same type of equipment and machines. These facilities are served (and linked) by a distribution system that uses trucks to move the raw materials, components and products between the factories.

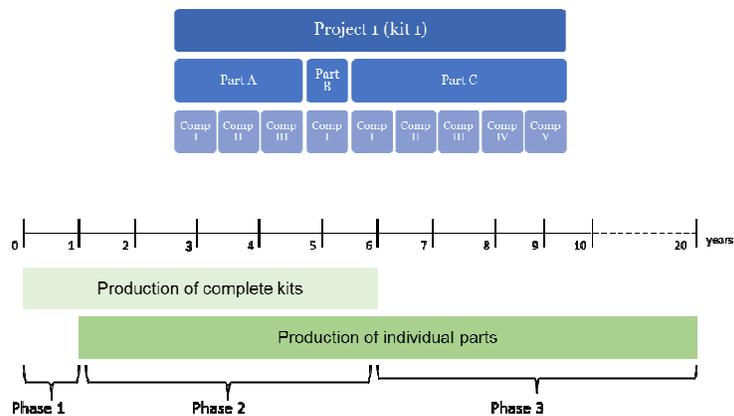


Fig. 1. Product complexity.

Given the high complexity of products, and the variety of requests from customers, in general collaboration between facilities is needed, with the formation of networks that change dynamically for each project.

In this context, our “collaborative multi-facility layout problem” involves the physical organisation of departments between and inside several geographically dispersed facilities, that collaborate in manufacturing a complex product in a given time window. The problem consists therefore in finding the best global layout for a given project. In order to optimise operations, we can use the flexibility of the system to exchange the location of departments between the facilities in different periods of time.

4 Model Description

The model developed in this work (Fig. 2) provides firms with the ability to dynamically modify or reconfigure individual business processes to accommodate their actual and potential needs [24] by determining the best layout configuration of each facility, taking into account the project needs in each period, the available production capacity and the transportation capacities between facilities. The model also considers the possibility, along time, of adding or closing facilities (departments and sites), thus creating the flexibility for firms to quickly respond, by continuously adapting to changing business environments [25].

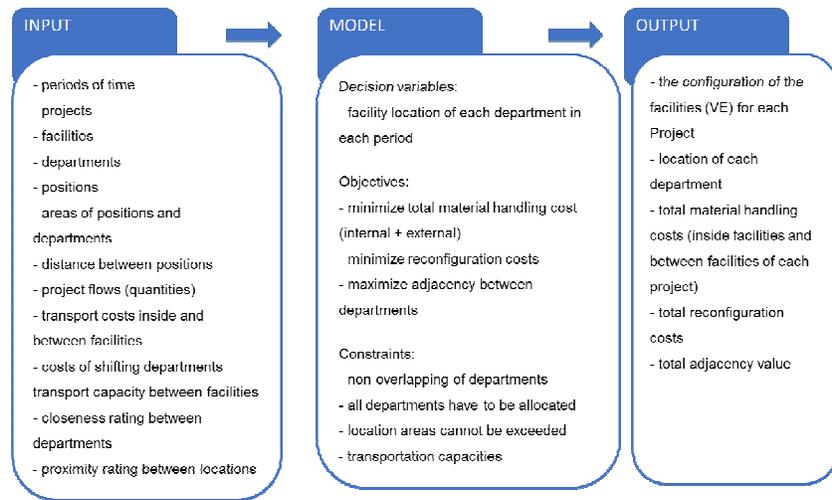


Fig. 2. Proposed model.

The formulation considered in this work is based on the Quadratic Assignment Problem (QAP), commonly used for dynamic layout problems [22]. Multiple objectives are considered, as defined by expression (1).

$$Min Z = \alpha MIIC + \beta RC - \gamma Adj. \tag{1}$$

The objective “minimizing the total material handling costs (MHC)” is commonly used in the literature of the unequal area FLP ([26], [27]). As [28] we assume fixed dimensions for facilities and the existence of several departments to be located inside facilities. We consider the total MHC as the sum of the internal and the external MHC

of each project. This model considers also the “*minimization of reconfiguration costs (RC)*” frequently used for layout reconfigurations (see e.g. [29] or [30]).

The objective “*maximization of adjacency (Adj)*” of the departments is based on a *closeness rating* (defining the importance of closeness between departments as proposed by [15]) and the *proximity* between the locations to where the departments are assigned. This is an important feature of the problem, due to the fact that when departments are allocated to different buildings, the relationships between them can be conditioned in different ways (e.g. imposing constraints on sharing the same specialized equipment or the same workers).

Our model adapts the constraints usually applied in the literature to solve unequal FLPs [21] to this multi-facility dynamic layout problem, namely: ensure that each position in a facility has at most one department, in each period; guarantee that each department is assigned only to one position, in each period; ensure that the area of a position is never exceeded by the department area assigned to it, in consecutive periods [20]; ensure that the existing capacity for transportation between facilities is never exceeded; check that the total number of existing locations is higher or equal to the total number of existing departments in each period; and confirm that only active departments are assigned to active locations in each period.

5 Computational Results

The performance of the proposed model was tested on some numerical instances based on a real case study briefly described below. Two situations have been considered, defined on the current case: first, by adding a new facility (test1); and, second, by closing one facility (test2). All the tests were made with the optimization software IBM ILOG Cplex V12.6, with a limit running time of 6 hours.

5.1 Problem Data

The case study motivating this work is based on a corporate group that produces plastic parts for the automotive industry. Initially ($t1$) there are 2 facilities ($f1$ and $f2$), and since $t2$ we consider a new facility ($f3$), with in total 13 locations to position the departments (Fig. 3). The distance between $f1$ and $f2$ is 30, as well as between $f2$ and $f3$; the distance between $f1$ and $f3$ is 50 unit of distance.

For executing the movements between departments, we consider a distribution (transport) system based on the following assumptions: *internal transport costs* are constant along time and do not depend on the distances (5 cost units / unit of flow); *external transport costs* vary with time ($t1=20$, $t2=22$, $t3=25$). The capacity of transport between facilities also vary ($t1=800$, $t2=1000$ and $t3=800$).

There are 5 different types of departments: raw material warehousing; injection; assembly; painting; and product warehousing (Table 1). Due to characteristics and organization of the production, the areas assigned to each department can change in each period. We also consider that there some advantages in having departments of the same type (e.g. injection – A, B, C) together in the same facility (closeness level equal to 5).

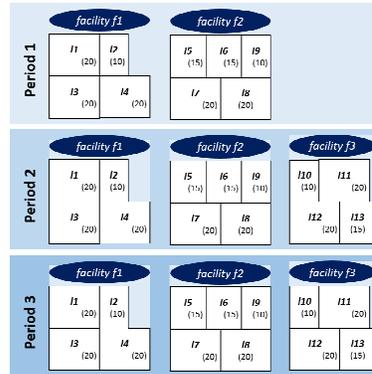


Fig. 3. Available area for the different facilities in each period of the horizon.

Table 1. Departments in the case study.

Departments	Raw material warehouse			Injection			Assembly			Painting	Product warehouse			
	A	B	C	D	E	F	G	H	I	J	K	L	M	
re-layout cost	5000			20 000			10 000			80 000	5000			
active departments	t1	0	1	1	0	1	1	0	1	1	1	0	1	1
	t2	1	1	1	1	1	1	1	1	1	1	1	1	1
	t3	1	1	1	1	1	1	1	1	1	1	1	1	1
area	t1	0	10	20	0	20	20	0	15	10	20	0	15	20
	t2	10	20	20	15	20	20	10	15	10	20	15	15	20
	t3	10	20	15	15	20	15	5	15	5	20	15	15	20

We consider there are 4 projects, in different life cycle phases: *project 1* and *2* have a continuous production along the planning horizon; *project 3* finishes in period *t2*; and *project 4* starts in period *t2* (Table 2).

Table 2. Project flows in each period.

Periods			Project	Flows between departments			
t1	t2	t3					
✓	✓	✓	P1	C -> F (500)	F -> J (350)	J -> H (200)	H -> M (200)
✓	✓	✓	P2	B -> E (100)	E -> J (150)	J -> H (150)	H -> L (50)
✓	✓	✓	P3	C -> F (100)	F -> I (100)	I -> M (50)	
✓	✓	✓	P4	A -> D (50)	D -> G (150)	G -> K (100)	

Concerning the relative importance of the different objectives, we have considered the following weights (that should later be subject to some kind of sensitivity analysis): 35% for MHC; 35% for reconfiguration costs; and 30% for adjacency.

5.2 Adding Facilities

The occurrence of a new project (P4) in t_2 allows us to explore the recourse to a new facility. Table 3 and Fig.4(test1) show the results obtained for this situation. Analysing these results, it is possible to conclude that:

- department J (painting) does not change along the horizon;
- facilities tend to become specialized in some phase of production (e.g. *facility 2* focus on Assembly, Painting and Product warehouse; f_1 and f_3 focus on the first production phases, with Raw material warehouse, and Injection; and f_1 at t_3 deals with all the product warehouses);
- *project 4* rotates among the 3 facilities, apparently due to the smaller quantities to be produced;
- flows inside facilities are naturally higher, because the distances are lower, and the capacity to transport is not constrained, as it is the case for the transport between facilities;
- external MHC costs (1 542 400) are considerably larger than internal MHC costs (34 500);
- there are 3 reconfigurations occurring inside facilities, and 10 between facilities, with a total reconfiguration cost of 165 000 and an adjacency value of 1015.

Table 3. Results of test 1 – adding facility f_3 at t_2 .

Project	Network structure	Flows inside facilities			Flows between facilities					total MHC
		f_1	f_2	f_3	f_1-f_2	f_1-f_3	f_2-f_1	f_2-f_3	f_3-f_2	
P1	f_1, f_2, f_3									650 150
t1	f_1, f_2	500	400		350					
t2	f_3, f_2		400	500					350	
t3	f_2, f_1		1050		200					
P2	f_1, f_2, f_3									373 900
t1	f_1, f_2	100	200		150					
t2	f_1, f_2	100	200		150					
t3	f_3, f_2		150	100				50	150	
P3	f_1, f_2, f_3									108 650
t1	f_1, f_2	100	50		100					
t2	f_3, f_2			200					50	
P4	f_1, f_2, f_3									444 200
t2	f_1, f_2, f_3					50	100		150	
t3	f_1, f_2, f_3			50			100		150	
		800	2450	850	950	50	200	50	850	1 576 900
Re-layout costs		165 000			Adjacency		1015			

5.2 Eliminating Facilities and Departments

In order to understand the impact of eliminating a facility, we will consider that *project 3* finishes in period t_2 (thus making departments B, E, I and L unnecessary) – see Table 4 and Fig. 4 (test2). Analysing these results, it is possible to conclude that:

- facility f_2 has always 3 types of departments for the last phases of production (Assembly, Painting, and Product warehouse);

- departments J and D do never change along the planning horizon; and departments B, E, M, H and K only change inside the same facility;
- flows (see Table 4) are similar to *test 1*, for each facility and between facilities;
- external MHC costs (1 399 900) decrease and internal MHC costs (11 650) decrease too, when compared with test1;
- this solution has less reconfigurations (5 inside facilities and 5 between facilities), with smaller reconfiguration costs than test1 (115 000), and a lower value of adjacency (895).

Table 4. Results of test 2 – close facility *f1* at *t3*.

Project	Network structure	Flows inside facilities			Flows between facilities				total MHC
		<i>f1</i>	<i>f2</i>	<i>f3</i>	<i>f1-f2</i>	<i>f1-f3</i>	<i>f2-f1</i>	<i>f2-f3</i>	
P1	<i>f1,f2,f3</i>								766 800
	t1	<i>f1,f2</i>	500	400		350			
	t2	<i>f3,f2</i>		400	500			350	
P2	<i>f1,f2,f3</i>								247 450
	t1	<i>f1,f2</i>	100	200		150			
	t2	<i>f1,f2</i>	100	150		150	50		
P3	<i>f1,f2,f3</i>								143 900
	t1	<i>f1,f2</i>	100	50		100			
	t2	<i>f3,f2</i>		50	100			100	
P4	<i>f1,f2,f3</i>								253 400
	t2	<i>f1,f2,f3</i>			150	50		100	
	t3	<i>f2,f3</i>		100	50			150	
Re-layout cost		800	2250	800	750	50	50	0	1050
Adjacency					895				

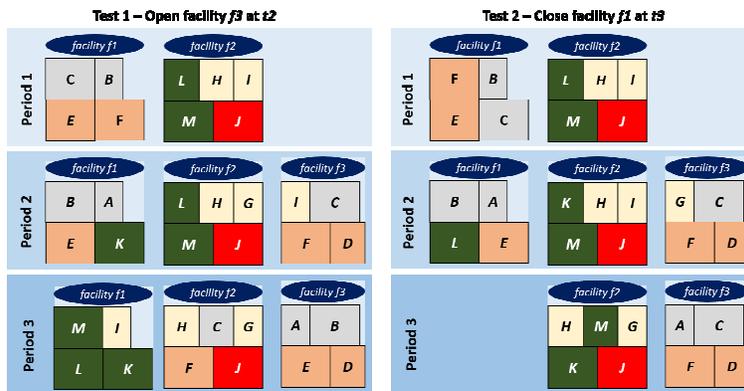


Fig. 4. Configuration of facilities, in test1 and in test2.

5.3 Assessing Network Collaboration

This model allows companies to evaluate, in different ways, the performance of the generated configurations: both for each facility and for the network formed for each project (in terms of flows, costs and time evolution) (see Fig. 5).

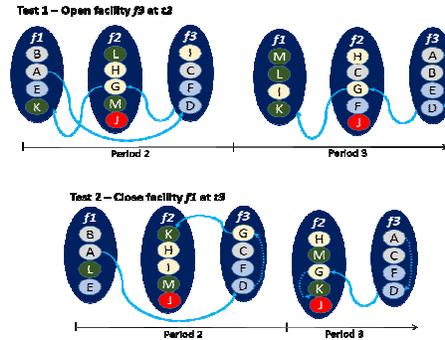


Fig. 5. Flows between facilities at Network of project p4.

Despite their preliminary nature, the results show the potential of inter facilities collaboration in manufacturing systems, and its role in dynamically adjusting the network structure to take into account the flows requirements in different periods of the planning horizon. These experiments also show the developed model can be used to adjust the firm's strategy in response to internal or external changes through facility layout collaboration.

6 Conclusions

This paper presents a model for supporting the definition of a collaboration strategy of different facilities or companies in a corporate group, to enhance its agility and responsiveness. For illustrative purposes, a case study was defined based on a first tier supplier in the automotive industry. The formation of collaborative networks involving the companies of the group may clearly improve manufacturing performance for the products and components of the different projects.

The model proposed in this work determines the layout configuration of all facilities, taking into consideration the flows between departments induced by the different projects. The model considers three objectives (minimize *total material handling costs*, minimize *re-layout costs*, and maximize the *adjacency* between departments) in order to better reflect the main prevailing concerns in real situations. The model was tested with two simplified instances inspired by real situations, namely: the emergence of a new project that requires a new partner; and the conclusion of a project leading to the end of that collaboration. These changes lead to the

implementation of some layout reconfigurations, in different periods of the planning horizon.

In general terms, the model can be used to support the design and deployment of new configurations and layouts, based on advanced forms of collaboration, and thus promote the strategic agility of a corporate group. This will allow a higher adaptability to customer requirements (better handling demand fluctuations or changing location of facilities to be closer to customers) certainly improving global performance.

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