XI. GRID FACILITIES DESIGN: DYNAMIC MODULAR DEPLOYMENT OF PRODUCTION, HANDLING AND STORAGE RESOURCES

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Abstract

To survive and thrive in a fast-moving environment, facilities must be designed to show adaptability, flexibility and robustness. As some facilities are depicted by heavy and sophisticated equipment costly and hard to displace, others are composed of moveable workstations with highly flexible workers. In most cases, the trade-off is between the cost of redeploying the resources and the excessive cost of material handling and storage incurred by an inefficient deployment of the resources. We propose a design strategy based on (1) conceiving and designing the facility as a stable grid of modules, (2) dynamically deploying production, storage and handling resources to these modules, and (3) dynamically assigning process-product combinations to the modules so as to meet stochastic and dynamically evolving product demand on a rolling planning horizon. We illustrate the strategy as applied to a computer refurbishing and recycling facility.

Keywords: Facilities design, Grid Design, Modular Facilities, Dynamic Design, Immune-to-Change Design, Robustness, Adaptability, Flexibility, Refurbishing and Recycling Facilities

1 Introduction

Designing a facility is getting ever more complex as product life cycles get shorter, response time expectations get higher, customization increases and, overall, product demand is becoming highly stochastic and variable in terms of both mix, seasonality and volume. Concurrently, designing facilities capable of high performance in such a context becomes critical in order to enable companies to survive and thrive. Adaptability, flexibility and robustness are becoming key design requirements for facilities to be dynamically efficient in such a fast-moving environment.

In the literature, two basic strategies are proposed to address these facility design requirements. The first is *dynamic facilities design*. It involves designing facilities that are thought from a dynamic perspective, with their organization, the resources and their layout known to be alterable through time, and exploiting this dynamics to alter the facilities so as to face the evolving context and requirements as best as possible. The core of the research along this approach has focused on dynamic layout [1], [2], [3], [4], [5], [6], [7], [8], [9]. When relayout costs are not significant, then the dynamic layout logic is simply to constantly assess the fitness of the current layout and potential alternative layouts in face of changing requirements, and to alter the layout whenever the relayout is assessed preferable to keeping the current one as the flow inefficiency increases. In most contexts, relayout costs are significant [6], [7], so the dynamic layout logic becomes to explicitly treat time-phased expected space and flow requirements, for example through dynamic scenarios [3]. This enables to design time-phased layout plans that allow the best compromise between the expected operating costs, such as material handling costs, and the relayout costs. This dynamic design strategy can be applied to most constituents of a facility, such as its material handling system.

The second basic strategy is *immune-to-change facilities design*, aiming to design a facility that is capable of high performance in a wide range of uncertain contexts with no or minimal alteration [7], [10], [11]. Two key examples of such designs are fractal and holographic facilities designs [12]. Fractal design [13], [14] consists of organizing a facility as a network of similar fractal cells, each capable of making most of the products and perform most of the processes within the scope of the facility mission, with a fraction of the overall capacity of the facility. Such a fractal facility deals smoothly with dynamic variations on product and process mix, and changing its overall capacity is achieved simply by activating or deactivating fractal cells.

Holographic design, also known as scattered or distributed design, consists of organizing the facility as a network of small holographic cells, each focused on some elementary function or process, which are replicated in multiple copies and strategically spread through the facility [10], [15], [16], [17], [18], [19]. At the operational level, this enables flow-efficient routings or virtual cells [20] to be dynamically generated for products or sets of orders as needed depending on the availability of the specific holographic cells. Contracting and expanding such a holographic facility is quite simple by deactivating some small cells within the holographic network and adding required cells in a distributed way in the fringes of the current network [7].

Immune-to-change design is particularly relevant for facilities where relayout costs are significant due to hard-to-relocate equipment and facility services. The researches previously presented for *immune-to-change* facilities are not exploiting the potential optional material handling systems and lot sizes for adjacent workstations. They are neither exploiting the flexibility of the production and storage resources and low relayout costs for specific resources within the facility.

In this paper we propose a novel strategy, *grid facilities design*. The strategy exploits some of the features of both the dynamic design and the immune-to-change design, yet differs significantly from these as it also expands from a well-known concept; modular facilities design [21]. In an integrated way, by introducing the grid facilities strategy, we notably aim to enable facility design modularity and adaptability. We propose that facilities be conceptualized and operated as a grid of spatially stable modules, to which are dynamically assigned resources and responsibilities given the resources availability, such as the number of workstations and material handling resources such as mobile conveyors.

Modular grid design aims at:

- Optimizing and stabilizing the physical structure of the facility: its shell, its grid layout of modular spaces and aisles, and its facility service networks;
- Dynamically altering the capability and capacity of modules through the fast and efficient deployment and layout of production, handling and storage resources into modules, as near as possible to plug-and-play;
- Dynamically assigning specific client, product, process and/or order realization responsibilities to modules, exploiting their adaptable capability and capacity;
- Dynamically resulting in fast response time, high service level, efficient resource utilization and efficient flow of goods within modules and between modules across the facilities.

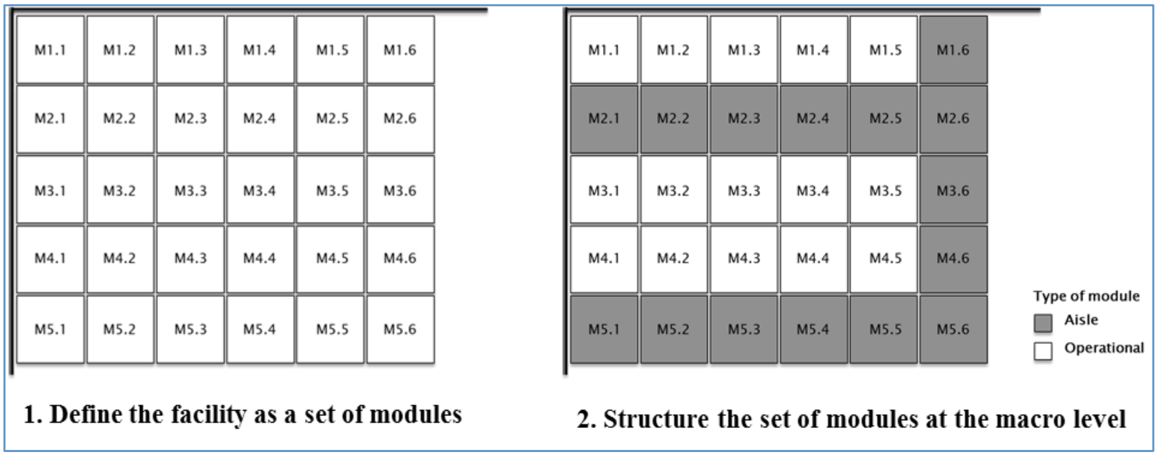
These concepts will be described in further details in the following sections.

2 Grid facilities design strategy

This section presents the concepts and underpinning of the grid facilities design strategy and it underlines its key design decisions. The proposed strategy exploits the fact that the facility is to be composed of workstations with various degrees of flexibility, capable of potentially performing several production processes on several products. The strategy designs the facility as a set of areas, called modules, having various size and shape. The left layout of Figure 1 shows a section of a facility defined as a set of 30 modules of identical sizes. These areas are depicted by characteristics such as height, services such as water and venting, etc. These modules are structured at the macro level, notably deciding which modules are to be used as aisles and which are to be used for operations, as shown on the right side of Figure 1.

The strategy assigns resources and defines the service capability of each module. The service capability of a module can be defined as the set of process-product combinations that can be performed in the module given its resource configuration. Service capability and resource configuration are thus tightly intertwined. Offering or not some services impacts the set of production resources, storage resources and handling resources required in the module. The offering impacts the operational responsibilities that can be assigned to a module, such as which product-process combinations are to be dynamically assigned to the module. Conversely, the set of production, storage and handling resources in a module impacts its service offering capability and its dynamic operational responsibility assignments.

A most flexible module would offer all pertinent services, as in a fractal design. In practice, it may well be infeasible or too expensive to achieve such extreme flexibility. In most cases, the flexibility stems from the overall network of complementary modules, each with a specific service capability and a specific set of resources. This enables to optimize production as demand changes through time by dynamically and smartly assigning operational responsibilities (e.g. production of a set of processes on a set of products for a set of orders) given each module's service capability, and altering this service capability as necessary by modifying the module's resource configuration.



1. Define the facility as a set of modules

2. Structure the set of modules at the macro level

Figure 1. Defining the modular grid structure of the facility

The grid facilities design strategy explicitly considers the key types of resources such as production, storage and handling resources. Relative to the storage resources, distinct types of storage units need to be explicitly recognized. Here are a few examples. At the smallest level, storage unit can be incorporated to a production workstation, such as a two-bin system for periodic replenishment of repair parts at a repair workstation. At the mid-level, short-term storage shelving resources can be incorporated into a module as it might be used in some modules that are predominantly production service oriented. At the largest level, entire modules can be devoted to storage service, with appropriate storage shelves, racking, stacking space, as pertinent, allowing to store more products over a longer horizon. The assignment and exploitation of these storage resource types has impact on batch sizes, utilization rates and material handling flow.

Figure 2 shows an example of two modules with their respective production (P), storage (S) and handling (H) resources, as well as their service capabilities. The first module is located on the upper left corner of a facility. Its production (P) capabilities are schematically indicated with a white box in the module showing the list of capabilities. Here they are simply identified in terms of which processes the module is equipped to support, inducing its capability to host production resources (e.g. workstations, equipment) actually capable of performing these processes on products. A large storage shelf (S) is located on the left side of module 1. Both modules exploit two types of material handling (H): conveyors enabling handling between these two adjacent modules, and material handling trough aisles. There is one potential conveyor link with the adjacent module to its right, as the potential link with the network of aisles is from the lower side. The link between the module and the aisle network is with I/O stations, here allowing transfer of pallets or shelves on wheels.

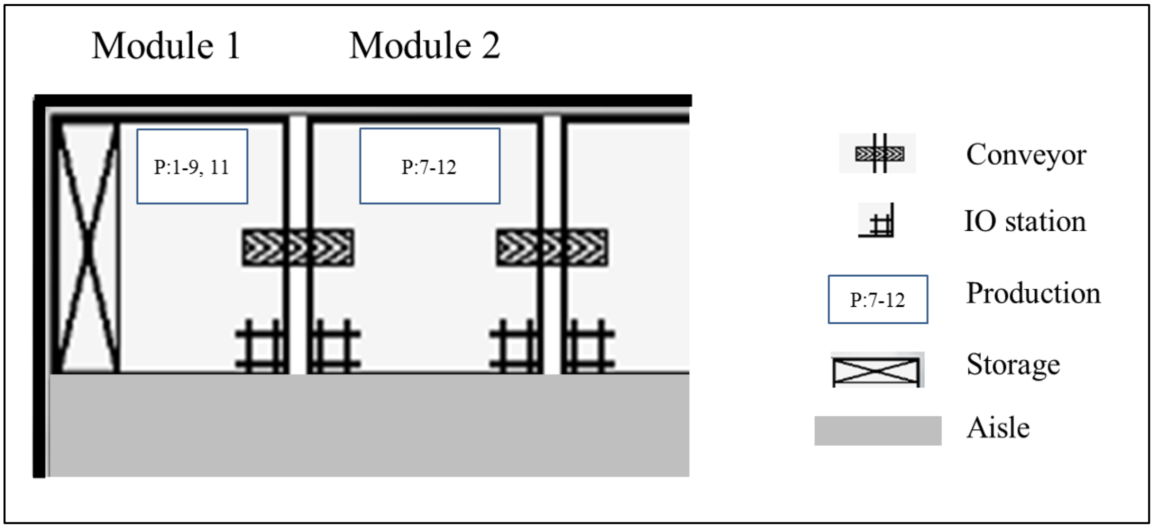


Figure 2. Example of modules with their capabilities

Figure 3 shows a larger section of a facility including several modules interconnected through the aisle network and/or through conveyors when the modules are adjacent.

The four goals specified in section 1 are interlaced. The set of production, handling and storage resources assigned to a module at a given time determine its capabilities and capacity, thus the kind of responsibilities it can assume. In the same order of ideas, the set of client, product, process and order responsibilities assigned to a module determines the capabilities and capacity it must have to robustly considerate these responsibilities [5], [12]. The layout of the modular grid defines inter-module proximity, affecting the assignment of capabilities, capacity and responsibilities to modules in order to enable efficient flow, as shown in Figure 4. It also shows the dynamics of the layout. Indeed, in the layout shown, the pink workstations have been added to the blue workstations of the prevision production period to enable the facility to answer the increase in the demand. Figure 4 illustrates the main product flow patterns between the modules as well as the selected location for the conveyors available to link pairs of adjacent module.

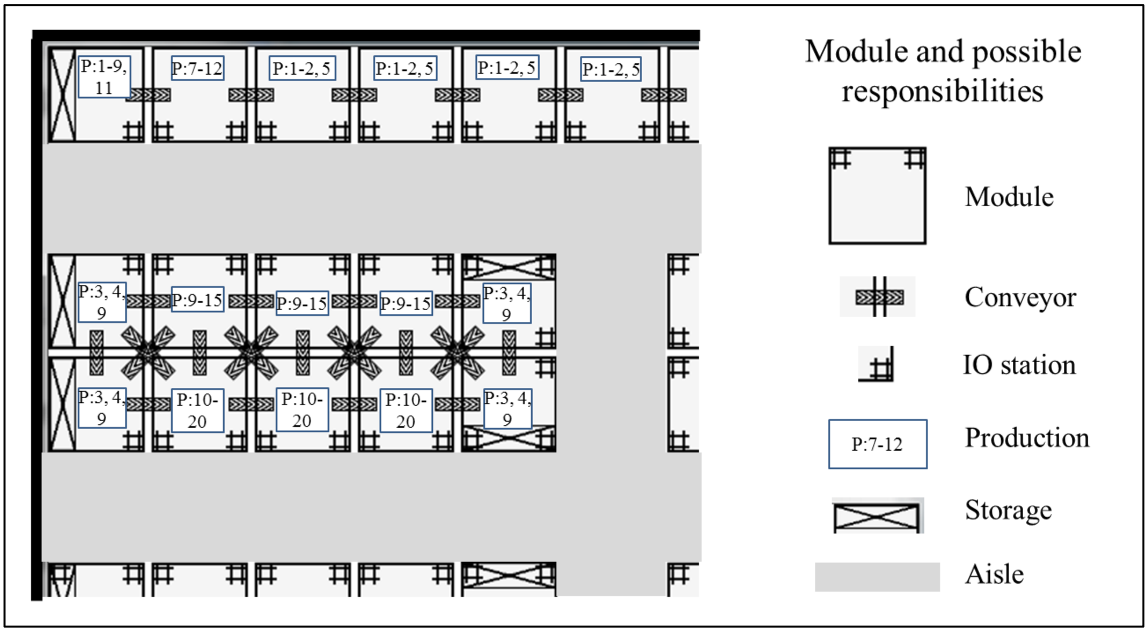


Figure 3. Modules with their capabilities on a larger section of the facility

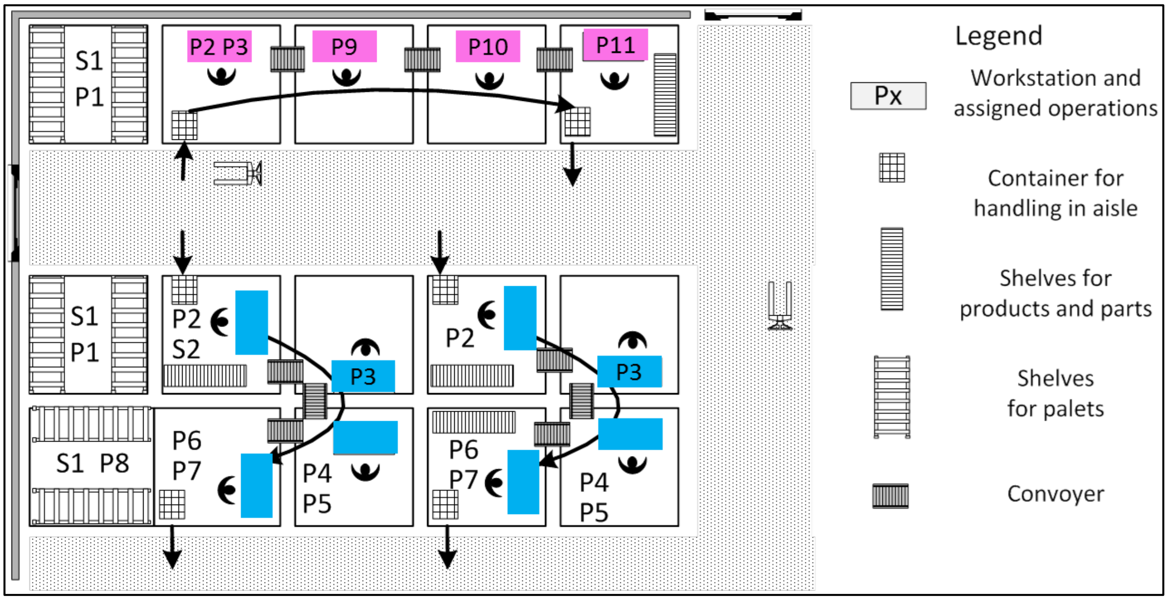


Figure 4. Illustrating the dynamics of resource assignment to modules and inter-module flow by focusing on the state at a specific period

In essence, the grid facility design strategy is based on three key pillars: (1) conceiving and designing the facility as a stable grid of modules, (2) dynamically deploying production, storage and handling resources to these modules, and (3) dynamically assigning process-product combinations to the modules so as to meet stochastic and dynamically evolving product demand on a rolling planning horizon.

3 Scoping the Grid Facility Design Problem

Grid facility design as introduced above is a challenging engineering design problem. In this section, we provide a description of the scope of this problem. There may be multiple variants of the problem, we focus on a wide scope version and define the goal aiming to be achieved, the key decisions and the design parameters and constraints to be tackled. The description builds on the works of Montreuil et al. [22, 23], Montreuil [7].

The goal is to minimize the expected total investments and operating costs for the facility over a planning horizon. The investment includes the building shell as well as the acquisition of all production, storage and handling resources through the planning horizon. The operating costs include the costs for producing, storing and handling products over the planning horizon, as well as the costs for relocating the resources from module to module at periods through the planning horizon. The key decisions to be taken are:

- The dimensions of the facility, and their evolution through the planning horizon;
- The set of modules, specifying the dimensions of each module, and stating their planned start and end of existence;
- The structural modular layout of the facility, defining the location of each module in the facility during their expected period of existence within the planning horizon;
- The resources expected to be assigned to each module at each period of planning horizon;
- The service capability of each module at each period of the planning horizon;
- The expected operational assignments to each module at each period, in terms of production, storage and handling.

The grid facilities design problem is inherently dynamic, addressed at a given time for a number of the future periods on a rolling horizon basis, provided the current state of the facility.

Relative to production, storage and handling resources, the input includes the set of resources currently deployed in each implemented module, the set of already acquired resources that are not at the moment deployed in any module, and the set of potential resources that can be acquired for deployment in the facility.

For each actual and potential resource, estimates are to be available for their acquisition, implementation, relocation, activation and deactivation as pertinent. Activation costs are incurred when reutilizing a resource after not utilizing it after at least one period of time.

Material handling is explicitly addressed in a grid facilities design. The dynamic deployment of handling resources is an integral part of the design process and, in grid facilities, handling resources that can be relocated seamlessly or at least at reasonable cost are preferred for exploitation. Relative to aisle-based handling, modules include input-output (I/O) stations that are well-delineated and re-deployable as necessary. These I/O stations are designed to ease the inbound and outbound flow of totes, pallets or movable shelves as pertinent, either by manual human handlers, human driven handling vehicles or automated vehicles. Sizing the team of human handlers and vehicles is part of the design process.

Some modules have to be defined as aisle modules and the network of such aisle modules has to insure access between any pair of modules having to exchange products through aisles. In the variable-path aisle network, products can flow in various forms and there must be adequate aisle and handler capacity to sustain the flow without excessive congestion and delivery delays. The handling is done in various lot sizes and these can be determined for example applying the approach introduced by Langevin et al. [24]. Relative to fixed path handling, resources such a conveyor can be used to ease the flow between modules. Between adjacent modules, conveyor segments can be deployed for conveying the inter-module flow, or robotic handling system can pass goods between the modules. Fixed-path handling resources can also be used between non-adjacent modules, as long as they do not interfere with the dynamic adaptability of the grid facility.

A key input to the grid facilities design process is the forecasted demand. As a basis lies the expected set of products to be produced/treated by the facility. Products are here defined at the appropriate level of granularity given their number and characteristics. For each product, the forecasted demand is input for each period along the planning horizon.

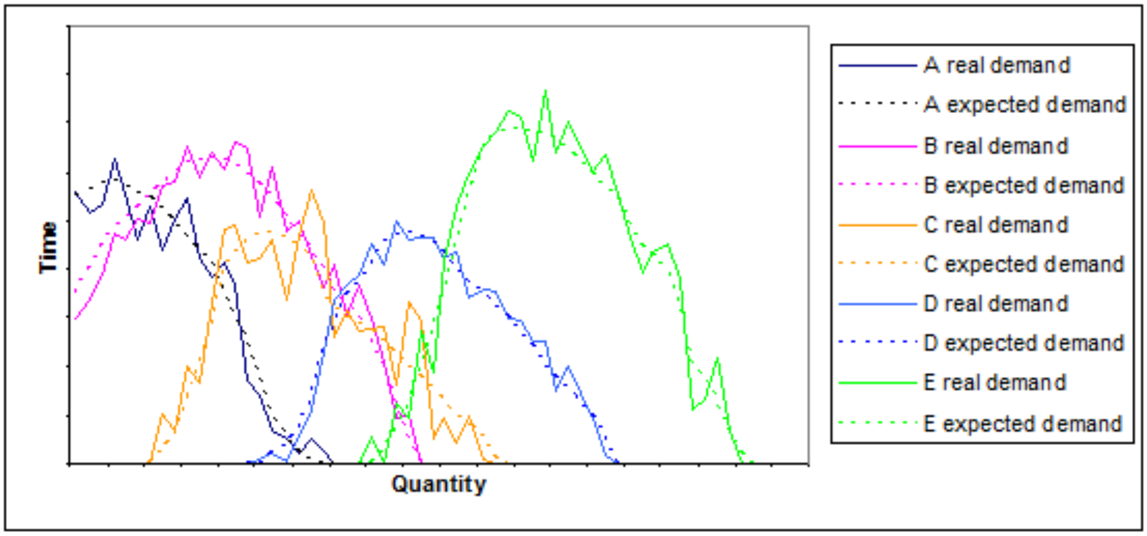


Figure 5. Probabilistic product demand forecast through the planning horizon

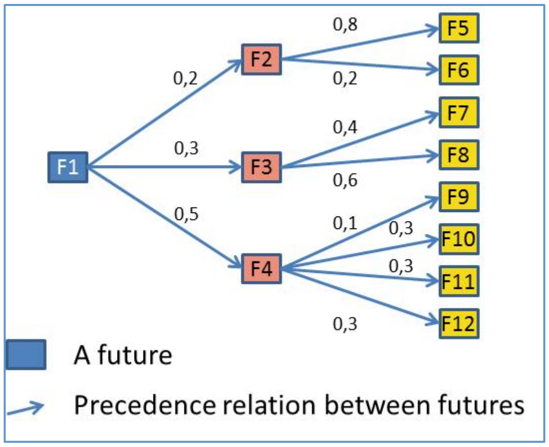


Figure 6. Probabilistic multi-future scenario based demand forecast

The product demand can be specified using a probability distribution for each product through time, as illustrated in Figure 5 where such forecasts are contrasted with the real demand that occurred (unknown at the time the forecast was made). Alternatively, probabilistic multi-future scenarios can be used. These specify a number of time-phased futures and probabilistic precedence relationships between them, starting with the immediate future, as shown in Figure 6. Each future provides demand estimates for every product during the future's existence as introduced in Montreuil and Laforge [3].

From a process perspective, grid facilities design requires dynamic input on the processes to be realized on the expected products. In a factory, this means having as input the manufacturing process for each product, expressed as a set of operations with precedence relationships, and the probability distribution of the operating time for each operation. If assembly or disassembly occurs, the bill of material is input, specifying how many parts of each type are required in an assembly or how many parts are to be expected from a disassembly operation. In the latter case, a probability of being functional is associated to each part, as well as the volume of raw material obtained from its disassembly.

The demand and process input is critical in deciding which resources should be deployed and activated in each module at each period, in determining the service offering of each modules in terms of capability and capacity, and in proposing time-specific production, storage and handling responsibility assignments for each module in terms of product-process combinations and quantities, thus defining the expected modular work-flow patterns and facility performance along the planning horizon.

4 Grid facilities design: an application

This section demonstrates an application of the grid facilities design strategy and methodology to a refurbishing and recycling facility case, building on the works of

Marcotte et al. [25, 26]. Refurbishing and recycling facilities face many challenges. Those challenges are acute when the products recycled have a very short life cycle, like electronic devices such as computers and smartphones. With short life cycles, the demand is not only stochastic but also very dynamic. Thus, a dynamic facility design is expected to offer a better performance. Fortunately, in many cases, most the workstations of a refurbishing and recycling facility can be moved to reduce expected future operating costs without incurring excessive relayout costs. This is especially true if the facility has been designed to ease its dynamic adaptation to evolving stochastic demand. It thus offers a sound test bed for grid facilities design.

The illustrative case is about a recycling and refurbishing facility that receives computers, either at end-of-use or end-of-life. The computers are sorted and treated to maximize the expected induced profit. They can be cleaned, repaired if needed and packaged to be sold. They can also be disassembled for their parts that can be used to repair other computers, sold as replacement parts or to a specialized recycler, or disassembled for the raw material. The process mapping is illustrated in Marcotte and Montreuil [27].

Figures 7 to 9 depict the evolution of such a facility trough time, focusing on the dynamic assignment of its three types of resources to modules: production, storage and handling. They show the relocation of the resources in the modules and their activation and deactivation as required by the changes in demand mix and volume. This evolution considers the future needs and the trade-off between relayout costs and material handling costs and efficiency. At any given point in time, colors are used to differentiate modules in terms of their active vs. inactive state and their change or not vs. the previous period.

The Figures show some of the main product flow patterns resulting from the flow optimization given each period layout. For example, Figure 7 shows the 45 modules activated for period 1. The other modules have been used in previous periods and/or are configured to be used later, but are not used in period 1, thus they are deactivated. Figure 7 also shows the assignment of the resources to the modules. In this layout, there are 7 modules with shelves, 41 mobile conveyors and 40 workstations.

The assignment of the available conveyors shown in Figure 7 minimizes the overall material handling costs with the available resources considering that additional resources could have been be bought according to predetermined cost of purchasing and installation. From these conveyors assignment, flows have been optimized and are showed on Figure 7 where larger lines correspond to higher flow. Two dark curves show the flow pattern of a product requiring more than one production resource for a given operation of its manufacturing process.

As the demand grows for some products in period 2, and decreases for some others, the layout of the grid facility in period 2 provided in Figure 8 shows the 11 additional modules that are activated (pink). Four new shelving has also been added for efficient storage material close to the point of use according to the needs. The layout of period 3 on Figure 8 shows that one module has been activated (16.2 on the left side) and two other modified (7.3 and 6.3 replaced by 4.2 and 4.3).

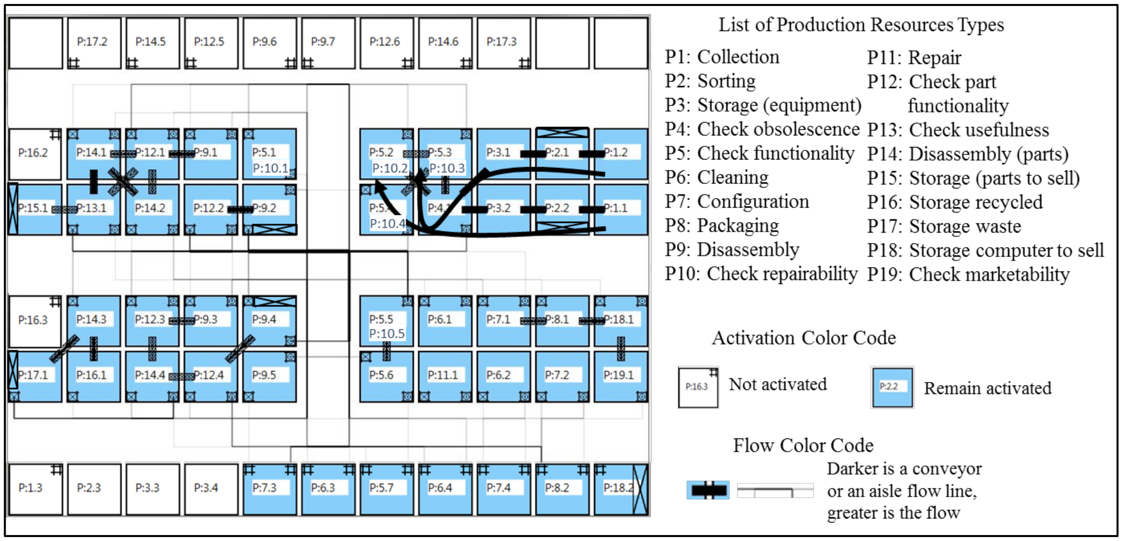


Figure 7. Layout of grid facility in period 1 contrasting activated and deactivated modules

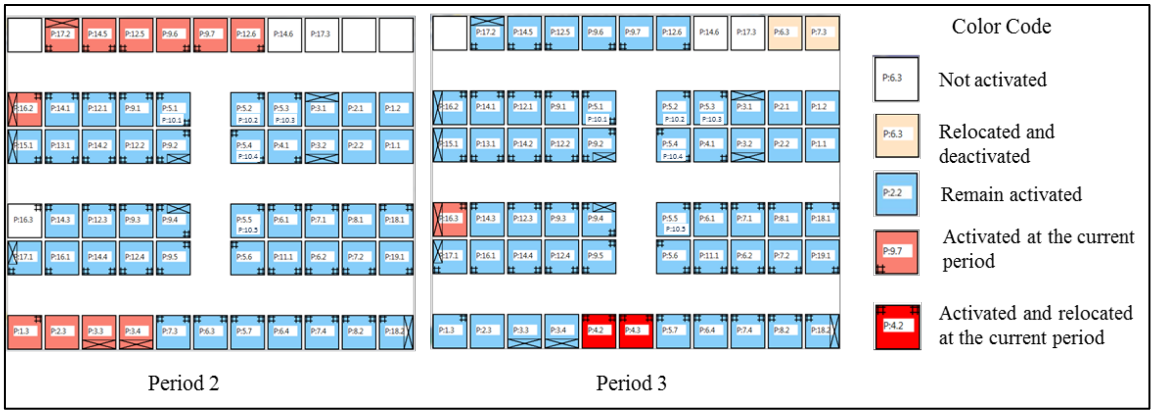


Figure 8. Layouts of periods 2 and 3, highlighting module activation and modification

Demand for a specific product (a computer with specific characteristics) may change regularly. However, globally, the demand for a specific process (like repair or disassembly of parts) might show less variability. In computer refurbishing and recycling in Canada, some companies do both refurbishing and recycling of a wide range of computer while others specialize as refurbishers or recyclers. It is thus most likely that, in some facility, a lower number of computers from a recent generation are expected to be repaired and/or recycled than computers from an older generation, as users are still satisfied and using the recent generation ones.

A similar observation can be made about much older computers that are to be disassembled for the parts or for their raw material, when the cost to repair it is greater than their value on the market. In such a context, a core group of modules might be stable and composed of the same resources through many periods, dealing with fluctuation on the mix of products as well as on the demand and offer volume for each of them.

Figure 9 shows, for the illustrated case, what happens to the grid facility when the demand decreases drastically in period 4: a core group of modules is left untouched while many modules are deactivated until further demand requires their reactivation.

This small case shows that the proposed grid facility design strategy is well suited for recycling and refurbishing facilities with highly dynamic demand and offer.

Figure 9. Grid facility layout for period 4, depicting deactivation of modules

5 Conclusions and future research

The main contribution of this paper is to introduce the concept and the underpinnings of the grid facility design strategy. The key idea is to conceive and organize the facility as a stable grid of modules in which can be dynamically deployed combinations of production, handling and storage resources, enabling to assign demand-satisfying product-process combinations to the modules and their embedded resources. This strategic juxtaposition of stable module grid, dynamic resource-to-module deployment and dynamic product-process assignment to modules and their resources enables the potential for facilities to smoothly and efficiently face the requirements to meet stochastic variable product demand. It enables facilities to be concurrently efficient, flexible, adaptable and robust. The strategy is original, transcending the current modular facility design strategy, the dynamic layout strategy and the immune-to-change facility design strategy. The strategy was illustrated for a refurbishing and recycling facility to insure its pragmatic and practical demonstration.

The paper has made explicit the key decisions at the core of the grid facility design strategy as it is applied to a case. In subsequent research, these decisions and the design constraints should be formalized into optimization models tackling them to generate grid facility designs evolving through a rolling planning horizon, based on specific context-based hypotheses. The models should represent formally dynamic decisions such as immediate and future resource-to-module assignment, module activation and deactivation, resource purchase, as well as flow and work assignment to and between module-assigned resources. The complexity involves not only many binary decision but a complex objective function where many variables that are dependant on one another. For example, the assignment of resources to modules depends on the expected flow between the resources while these flows depend on the location of the resources, which in turns depends on their assignment to modules.

Context-based hypotheses leading to distinct models include linear vs. complex assembly and/or disassembly processes; restricting to single production resource per module vs. allowing multiple production resources per module; a fixed set of resources vs. allowing altering the set through acquisitions, sales and terminations of resources; deterministic vs. stochastic demand; treatment of end-products only vs. explicitly modeling parts and materials; static building or adjustable building; the treatment or not of the impact of decisions on lead times for shipping orders to clients; as well as cost minimization vs. profit maximization through impact on sales; limiting to a single facility or tackling a network of grid facilities.

On one hand, key sets of hypotheses are bound to make a model amenable to exact solution up to optimality for moderate-size cases, while other sets are to require relying on heuristics, metaheuristics, matheuristics and/or simulation-optimization approaches to generate optimized solutions to the model. This opens a wealth of potential research avenues.

On the other hand, practicing engineers have to tackle the reality of their context, even though supporting models address all constraints they are facing and all decisions they have to tackle. This leads to the need for further research on developing and testing comprehensive design methodologies capable of supporting the engineers in implementing the grid facilities design strategy in their facilities. Such methodologies should exploit as best as possible optimization and simulation whenever pertinent.

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