Design of self-contained, adaptable factory modules

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Abstract
Fast changes in customer needs and continuously new product trends define increasing requirements for the flexibility and productivity of modern industrial plants. Production systems of the future are able to handle the increasing complexity and the shorter product life cycles. Their agility offers new opportunities to the companies. The concept of production modules helps management and planners not only to achieve the targets of high productivity, short delivery times and high quality but also to minimise the risks of wrong sales forecasts, high fixed costs, low flexibility for variants and quantities and liquidity problems in financing.

Keywords
Agile Factory, Supply Chain Design, Modularity, Material Flow, Risk Minimisation

1 INTRODUCTION

Against the background of increasing customer requirements, shorter product life cycles, international product-, procurement- and sales-markets, as well as the increasing cooperation of companies through better exploitation of the Internet, the requirements of the factory of the future can be summarised as follows [1]:

- Customer oriented (individual products, short delivery times)
- Productive
- Flexible (innovative in products and processes, assurance of investments)
- Organised in a cooperative manner through networks

Some companies have already reacted to these new requirements. In order to get a more concise idea of this phenomenon we have performed an empirical study to identify the most promising trends in future factory planning.

1.1 Trends in modern factory planning

1.1.1 Produce to flow principle

A very important trend in factory and production system planning is the strict orientation on material flow. Lead time reduction has become one of the most important objectives for management in order to meet the shortening order-to delivery times and to minimise risks and costs and even quality problems by reducing the work in progress. Continuous flow is the most efficient way to produce and the best solution to eliminate the different sources of waste (e.g. overproduction, unnecessary transport, unnecessary movement or handling, workers waiting, and so on). Nevertheless, there are many practical examples in industry where continuous flow is not possible and batching is necessary. This happens where processes are designed to operate at very fast or very slow cycle times and need to change over to serve multiple product families. Other processes, such as those at suppliers, are far away and shipping one piece at a time is not realistic [2], which leads to the next trend:

1.1.2 Integrate supplier on site

A very noticeable trend in factory planning is the integration of suppliers in the same plant site. In this way, costs for external transport, packaging, handling and other non value adding activities can be avoided. On the other hand, lead time is reduced which has a very positive impact on flexibility and can reduce material stock, eliminate incoming goods inspection and react quickly to quality problems. An interesting alternative to physical integration of suppliers on site is the introduction of consignment stocks, which is basically a supplier's finished goods inventory on the customer's site. In such an agreement, the supplier provides a minimum stock on the customer's site and has to make sure that the customer never runs out of material. The customer provides storage space and carries the inventory costs.

1.1.3 Reduce complexity

Three important core concepts are frequently applied for complexity reduction. The first is the separation of complex and individual production processes from standard processes. In this way, the cost efficient flow principle may be applied for standard production, while individual products are manufactured in separate segments. The second concept provides complexity reduction by dislocating variant generation to the line end, to shipping or even to sales. Thus, production and supply chain management can be simplified significantly. The third trend embraces the frequently discussed platform concept which allows the segmentation of production according to the similarity of products, modules or components. Synergy effects in manufacturing and assembly within product or component families can be realised.

1.1.4 Realise autonomous units

The concept of the modular factory is still a very relevant approach to the planning of new factory sites. The basic idea of this concept is to assemble a factory with flexible, self-regulating and product-oriented production modules aiming at a reduction of management and controlling effort through autonomous units [3]. This requires more self-responsibility of the workforce and an extension of their competences as well as a clear definition of the interfaces between the independent modules in an internal customer-supplier-relationship. A frequently applied solution is to design the system borders of an autonomous production unit according to the need of introducing supermarkets where continuous material flow is not possible and batching is necessary.

1.1.5 Keep innovation close to production

Another significant trend in factory planning is to provide innovation zones near the regular production flow, for example to test new products or technologies in the normal manufacturing environment. Thus, product developers receive direct feedback from the manufacturing staff and can make valuable experiences with new processes or materials in small series and mostly manually designed processes and can therefore minimise risks at a very early stage of the innovation process.

1.1.6 Maintain flexibility

A very important challenge in factory planning is the realisation of flexible capacities for balancing variations in demand and for a better utilisation of machinery and equipment. Besides the implementation of different concepts for working time flexibility, planners actually try to meet these requirements combining different manufacturing and handling technologies with different levels of automation in modern production systems. Especially a trend towards hybrid manufacturing and assembly systems can be identified with higher requirements for the workforce regarding qualification, work autonomy and responsibility.

1.1.7 Standardise proven concepts

Many companies tend to standardise technological and organisational concepts in a so-called “Production System” aiming at an easy transfer of know-how through proven standards to other production sites. Typical elements of such Production Systems are teamwork, TPM, CIP, quality management systems, problem solving techniques, visual management and standardised material supply systems. [4]

We can summarise: The factory of the future has to be versatile and able to react quickly and adapt to changes at a minimum cost of investments. But what methodological approaches can be derived from these requirements for the planning of a modern factory?

2 LESSONS LEARNED: DESIGN PRINCIPLES

On the basis of insights from the analysis of best practice solutions in factory and production system planning, the following **10 design principles** for the planning of self-contained, adaptable factory modules could be outlined as follows:

- Clear cut **assignment of product families** to the factory module (own “product spectrum”)
- Strict **orientation to flow principle** to achieve a maximum productivity
- **Autonomous management** of production units regarding order processing, setting priority rules and material supply
- Complete autonomy in operation as an integral part of in-house production or in a model of external operated parts manufacturing, as **suppliers on site** or as supplier operated consignment stocks
- **Variant flexibility** determined by process sequence and lead time of the single items
- **Volume flexibility** by working time flexibility and agile production systems
- **Complexity reduction** by separation of complex and individual production processes from standard processes, by dislocating variant generation to the line end and by realising platform oriented product concepts
- **Structural flexibility** to enable volume and variant flexibility and to allow continuous process innovation with low investments
- **Replaceability** by creation of flexible interfaces (best there, where the continuous flow is interrupted and changes in the continuous material flow are unavoidable)
- **Standardisation** of proven concepts

3 INTRODUCTION TO THE CASE STUDY

The following chapters illustrate the concept of self-contained, adaptable factory modules with the practical example of a manufacturer of prefabricated bathroom pods. The company started as a small workshop producing prefabricated bathroom pods especially for the growing local hotel business. The idea was to shorten restructuring times of hotel buildings delivering industrially built bathrooms just in time to the construction sites. In addition, the quality of the product could be improved by having a continuous production process with industrial levels of quality assurance. Basically, the first product concepts provided a raw pod assembled with glass fibre reinforced plastic panels (GRP panels) and then equipped with standard fittings available on the market for bathroom installation. In this way, the company developed a unique know-how in the conception, manufacturing and assembly of GRP components. However, the international extension of activities to other market segments in the following years required an update of the applied materials and led to concepts including for example steel frame constructions with different sandwich panels. However, the variety of material combinations and the quickly changing design and material trends made it difficult to define the right concept for a new larger factory site.

4 THE CONCEPT OF FACTORY MODULES

4.1 The system "Factory Module"

What does a factory module look like?

According to system theory a factory module can be defined as a "black box", with defined attributes and with assigned processes and resources. It has interfaces with the environment and can receive input and send output in form of material, information and energy [5]. Ideally, a module has a kind of plug which makes replacing it easy with another compatible module.

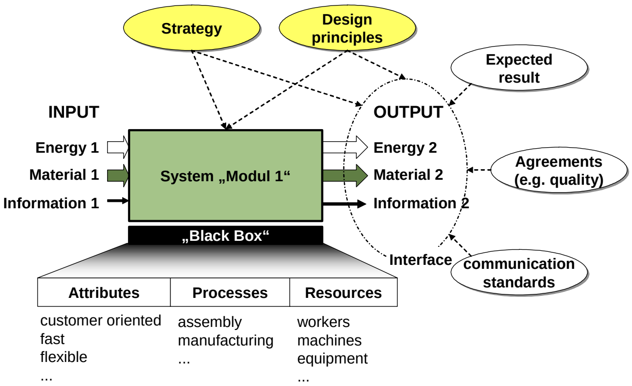

Figure 1. The "Factory Module" system [1]

To define the interfaces and service level agreements between different factory modules it is helpful to know exactly the module's environment integrating it into the company's complete value stream.

Figure 2 shows a generic example with a defined expectation of Factory Module 3 towards the output of Factory Module 2. The internal process design of Module 2 and the output of Module 1 have an impact on the input interface of Module 2. Looking at the entire system of a company's value stream, these interactions can be identified and help together with a strategy for future development of the system and with the above outlined design principles to define the design parameters of the factory modules.

In order to guarantee the interchange ability of a factory module, environment and the company's market, product and technology strategy have to be considered. The same is true for the internal design of a module.

System theory provides a set of hierarchical systems and their sub-systems. Every system therefore contains a network of sub-systems, which also have to be designed according to the above design principles.

4.2 Select suitable Innovation Families

Common to nearly all concepts of modular factory and product oriented organisation is that the design of production segments is strictly oriented to product groups or product families. In this context, not the long term strategic and technological development of product and production technology is considered but rather the current status and its projection to the near future. However, the knowledge about future development of products and manufacturing technologies as well as the connected core competences of the company are important prerequisites for the design of self-contained, adaptable factory modules. In such a case, we do not talk about product families but about so-called innovation families.

Innovation families are combinations of products and technologies which represent the company's actual core competences and project it to the future along the imagined development of market and technology trends. These scenarios help to identify future changes and to consider these trends in factory and production system planning.

The approach to identification and the design of innovation families as the basis for further factory module planning will be discussed in the following chapters.

4.2.1 Identify core competences

Before starting to plan a new factory site, the company's strengths regarding technologies, resources and organisational know-how have to be clearly outlined. This is important to make sure that future decisions regarding production systems, technologies and layouts reflect the core competences of the company and therefore will guarantee the long term effectiveness of investments.

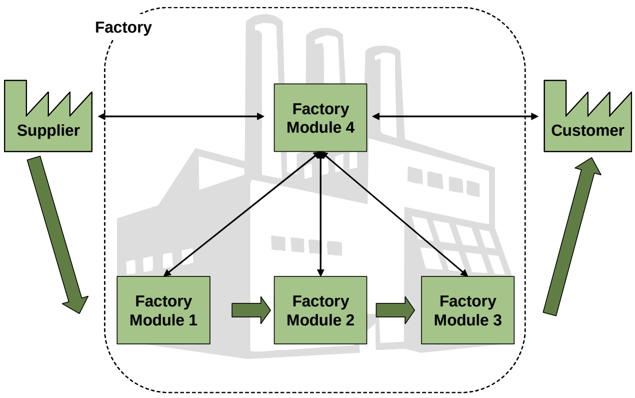

Figure 2. Factory Modules within the company's value stream [1]

The analysis of the core competences should evaluate the product concept, the applied technologies and the own available resources according to the following aspects:

- Easy or difficult to obtain on the market?
- Easy or difficult to replace/substitute?
- Immobile (tied to the company or location)?

The analysis of pod manufacturer shows core competences in three fields of activity:

- GRP manufacturing regarding process know-how, technologies and available resources
- Pod assembly regarding high efficiency of process and resources

Another important core competence is of course the conceptual know-how of the entire product.

4.2.2 Develop strategic technology scenarios

The currently applied technologies are analysed as to their future importance for the company's products and manufacturing processes. The example of the pod manufacturer (Figure 3) shows that the current main technology GRP will lose importance and will be partly substituted by alternative materials and technologies (e.g. wall panel, roof panel and shower). However, it will keep its importance for the floor panel, because a serious alternative couldn't be identified on a functional and cost perspective for the next 10 to 15 years.

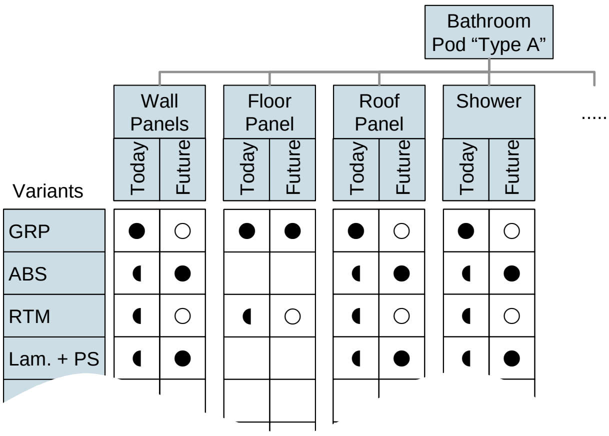

Figure 3. Example of a technology scenario

For a factory module this means that GRP - although in future applied for fewer components - will maintain its "primary" function as a strategic core competence of the company for a reasonable long period. As sales perspectives for the next five years are very good, the expected increase in revenue will balance the overall reduction of GRP parts and maintain or even slightly raise the demand for GRP.

The second production related core competence is pod assembly. Although recent developments towards higher costs of transportation (fuel, tolls) make it necessary to rethink the transportation policy, assembly as production competence won't lose its importance. Remember the sales argument of a prefabricated bathroom: short construction times, punctuality, fewer costs through economies of scales and industrial processes. An interesting compromise is the building of sub-assemblies: these are compact and still easy to install.

4.2.3 Find suitable autonomous production units

In this step, all products and variants are compared with their relative manufacturing and assembly processes and clustered according to similarities within the process pattern (Figure 4). A product cluster's yearly production volume must be sufficient to justify its own production unit. Otherwise, it has to be combined if possible with another cluster or eventually be outsourced. This topic will be picked up later on.

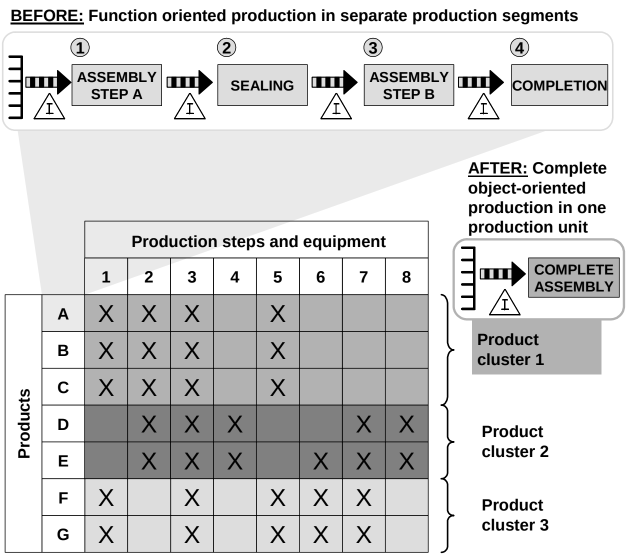

Figure 4. Example of product-process clusters

On the other hand, not every cluster that fulfils the minimum volume requirements is automatically an ideal autonomous production unit. Process related characteristics might have a further influence on its right segmentation. Thus, before finally defining an autonomous production unit processes within a product cluster have to be analysed and designed.

There are three fundamental principles to design the processes of a product cluster: object orientation, process orientation and combinations of both.

In an object oriented design all process steps of a cluster are combined in just one production unit. This design type will be selected, if lead times of the single process steps vary widely. Variant flexibility is achieved through the flexible design of a single work place or work station, volume flexibility by reproducing these work stations according to the demand situation. This obviously requires also a (simple) structural flexibility, as shown in Figure 5.

However, in a process oriented design flow principle plays a predominant role. An important prerequisite for pure process orientation is a variant independent relative proportionality of the single process lead times. This way, volume flexibility can be achieved by capacity balancing within the single process steps. In alternative, main processes can be shortened to a variant independent flow, while the creation of variants is bundled in sub-processes. In this case, volume flexibility is achieved by simple line balancing in the main flow and by flexible capacity control in the sub-processes. Common to both variants of process orientation is structural flexibility, which has to be realised vertically to the main material flow.

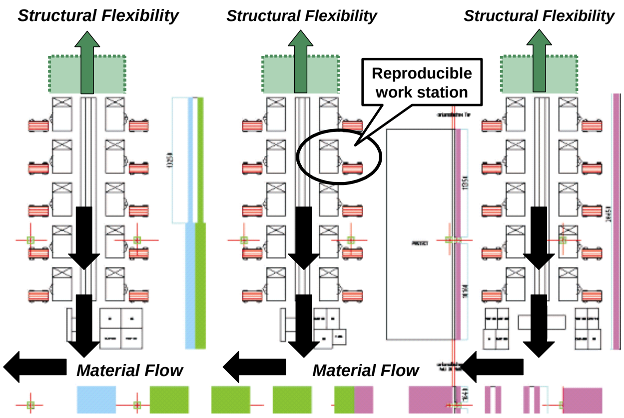

Figure 5. Structural Flexibility through reproducible work places [7]

The combination of object- and process-principle refers to the design principle of the autonomous units, outlined in chapter 2.

A smooth transition between the two principles requires the buffering of semi-finished products or components. The autonomous management of the material supply between customer-process and supplier-process requires a clearly defined link between two separate production units, for example by a supermarket-pull-system.

In this case, separate production units within the same product cluster might be useful.

In our example of the prefabricated bathroom pods the following production units could be detected:

- Module 1: Manufacturing of GRP panels (process orientation)
- Module 2: Pre-assembly of the bathroom pod (object orientation)
- Module 3: Final assembly of the standard bathroom pod including the assembly of all fittings, electrical and hydraulic installation, final testing and packaging (process orientation)
- Module 4: Final assembly of individual bathroom pods including the assembly of all fittings, electrical and hydraulic installation, final testing and packaging (object orientation)
- Module 5 (optional): Manufacturing of sandwich wall panels (currently delivered by external supplier)
- Module 6 (optional): Manufacturing of ABS parts for the shower (currently delivered by external supplier)

4.2.4 Define the right Innovation Families

Finally, the results of the three previous steps have to be combined to form Innovation Families. The identified single production units are now analysed regarding their strategic importance for the company and their future development according to the previously developed strategic scenarios.

In our example, the company's core competences are focused on GRP production, pod assembly and the assembly of shower doors in the sister plant (chapter 4.2.1).

In chapter 4.2.2 the strategic analysis showed that GRP will keep its strategic relevance for the company in future, but will be applied just for the floor panels. Other parts like wall and roof panels which had been previously produced in GRP will now be replaced by other materials outside the company's core competence profile.

For GRP parts therefore, the company decides to keep its production for floor panels and redesign it even more efficiently as one-piece-flow (design principle "orientation to flow principle") concentrated on a reduced standard spectrum of components (design principle "complexity reduction"). The original GRP process included the complete flow from raw material to the pre-assembled pod, with buffers between GRP manufacturing and pre-assembly.

According to the design principle "replaceability", GRP manufacturing (Module 1) and pre-assembly (Module 2) were assigned to different autonomous units (design principle "autonomous management"). With this clearly defined interface it is now possible to outsource the current GRP manufacturing for the wall and roof panels and the shower to external GRP manufacturers or to suppliers of other materials, such as ABS or sandwich panels (Modules 5 and 6 work with consignment stock, see design principle "suppliers on site").

Final assembly is subdivided in two different modules according to the "complexity reduction" design principle. Module 1 cares about standard pods in a strictly process oriented assembly line, in Module 2 special pods are assembled in the object oriented way using material carriers with commissioned pieces that are brought to the assembly station.

4.3 Determine the future Factory Modules

Recapitulating, a Factory Module is a system with defined inputs and outputs, with characteristic attributes, processes and resources that are arranged according to the module's integration in the company's value stream and considering the company's general market and technology strategy.

The Innovation Family is the strategically defined product spectrum of the Factory Module as an autonomously managed "factory in the factory".

We can summarise that every Factory Module

- can be managed autonomously, as an integral part of in-house production or in a model of external operated parts manufacturing, as suppliers on site or as supplier operated consignment stocks
- is strictly oriented to flow principle
- can be flexibly extended at any time (structural flexibility as one major prerequisite for volume and variant flexibility)
- might be replaced by another module with the same or at least with similar interfaces
- fits perfectly into the company's entire value stream

With these prerequisites, in the next step a plan by stages can be developed for the stepwise assembly of the identified Factory Modules (Figure 6).

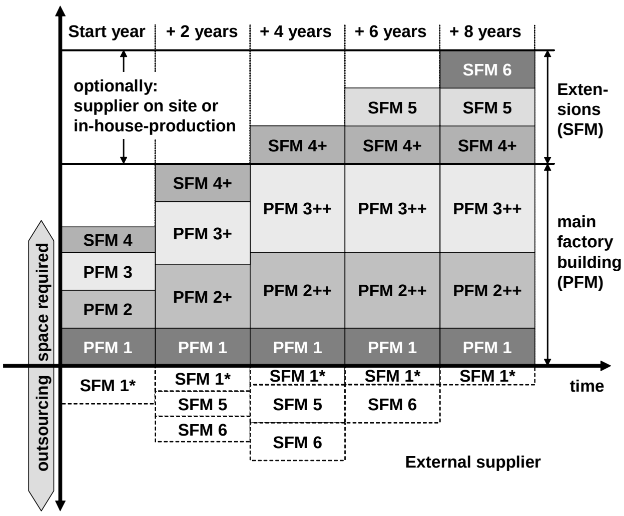

Figure 6. Scheme for graduated extension with Factory Modules

For this purpose, we differentiate between "Primary Factory Modules (PFM)" and "Secondary Factory Modules (SFM)".

A PFM performs a strategically important production activity containing core competences of the company. Considering the strategic relevance of a PFM, it will be considered among the most important factory functions to be realised. As PFM are expected to have a long life-time they are located in those areas of a factory which are programmed to have less structural changes within a plant site. Nevertheless, space for structural extension of the PFM has to be provided.

Ideally, PFM are located close to central functions like maintenance, production management and – last but not least – product development (Figure 7).

As PFM are based on important Innovation Families, they should allow continuous process innovation without major restructuring efforts and therefore with low investments (see design principle "structural flexibility"). This way, also a better information exchange and feedback between manufacturing and product development can be achieved, which is one of the most important success factors for the innovation process of the future.

A SFM does not contain any strategically important activity and might therefore eventually be outsourced (outside plant site or with the supplier on site) or even replaced by another SFM for example in the case of a substantial technological or material related change in the SFM's production spectrum.

SFM are possibly subject to short or medium-term changes and are therefore located in those areas of a plant site that are most suited for structural changes (regarding buildings, equipment, infrastructure, etc.). As SFM might be operated by external suppliers, clear cut interfaces to the other factory modules should be defined.

In the example of the pod manufacturer, three PFM were defined: GRP manufacturing, pre-assembly of the pod and final assembly of the standard bathroom pod. Final assembly of individual pods, ABS manufacturing and sandwich panel manufacturing are not strategic core competences and were therefore defined as SFM.

To allow a stepwise investment policy, two development stages were defined for the new factory building. The first construction unit contains just PFM which can be flexibly adapted to demand variations. According to the business plan, PFM 2 and PFM 3 will be extended in two steps, after two and after four years. PFM 1 will be kept stable over time, eventual increases in demand will be absorbed by external suppliers (SFM 1*).

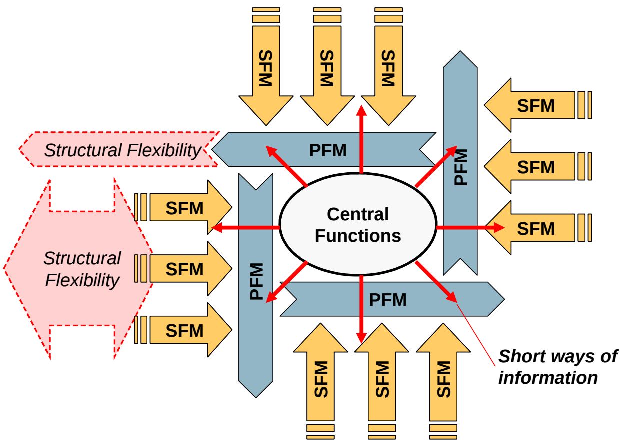

Figure 7. Layout example for maximum structural flexibility

After four years, the main factory building will contain just the three PFM. In the case of the company's positive economic development, the second construction unit can be activated at this point in time. It will absorb secondary factory functions (SFM), optionally by producing them with their own resources (in-house-production), with suppliers on site or even with consignment stocks managed by external suppliers. The decision on this will depend on prices and available capacities.

5 CONCLUSIONS

Manifold experience with different planning objects has proven the success of the design method with self-contained, adaptable factory modules. The increase in flexibility and adaptability of the companies to market fluctuations whilst increasing productivity and shortening the material flow has been shown in the past. Especially with regard to green field planning of factory locations this method keeps the investment cost at a minimum or variable. At the same time this design helps to structure the whole process over a certain timeframe so that the financing of the project does not compromise the liquidity of the company at any time.

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8 BIOGRAPHY

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