Factory Production Line as SoS; a Case Study in Airplane Engine Component Manufacturing

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Abstract - *Factories are examples of system of systems with all related problems of integral ownership, lack of overview, emerging properties, and many stakeholders making decisions locally. In the past 7 years, engineers at the GKN Aerospace factory in Kongsberg have been modeling parts of the factory to tackle the complexity of such a facility. In successive papers, they have shown that modeling helps in understanding, reasoning, communication, and decision making. In this paper, we zoom out and describe from a systems of systems perspective the challenges of modeling the system to improve factory level performance indicators, such as inventory levels and production cycle times.*

Keywords: Manufacturing, Factory, Systems-of-Systems, Modeling.

1 Introduction

Factories are a typical example of systems of systems. A factory is an operation running production machines, transportation and storage systems, and several layers of automation systems. A complication in factories is that many humans interoperate with machines and other humans to manufacture products.

The case study focuses on a Turbine Rear Frame (TRF) production line in a factory from GKN Aerospace Norway (GAN). GAN produces parts for air plane engines, such as vanes, see Figure 1. The factory is a complex manufacturing system, full of complex machines (for example for welding or drilling), accurate measurements systems, human experts, information systems, and facilitating services. Figure 2 shows an example of a production line for airplane components as modeled by Stalsberg [1]. In this factory many different parts are manufactured concurrently. The production equipment is capital intensive. Consequently, production of various parts shares the use of expensive machines. Traditionally, the production planning and design of production line maximizes the machine utilization. Modern insights, such as LEAN manufacturing [2], trigger questions about other key performance parameters, such as cycle time and stock size. Gustavsson [3] reports from his Japanese research trip that the origins behind Lean tend to be more philosophical, for example using terms such as harmony, than the analytical Western interpretation that Lean offers. However, both from the Leanish perspective as well as from the more philosophical viewpoint, questions arise about the utilization oriented manufacturing approach.

Figure 1, The CFM56 engine, produced by SNECMA, that powers aircraft such as Boeing 737 and Airbus A318/A319/A320/A321/A340. GKN Aerospace Norway produces low pressure turbine case, low pressure turbine vanes.

For the last few years, GKN Aerospace has employed a few industry master systems engineering students each year. These students have modeled and analyzed [4] parts of the GKN factory in their courses and master projects (see [1, 5, 6, 7]). Especially during the Modeling and Analysis course (SEMA)[1], the GKN students modeled parts of the factory. The response on these modeling efforts in general is quite positive. However, when co-author Andersen modeled part of a production line recently in a LEAN drive, we observed a lack of progress in achieving the goals. In this paper, we reflect on current hurdles that, according to our analysis, find their root cause in the Systems of Systems nature of a factory.

[1] All course material for this course is available online at http://www.gaudisite.nl/SEMAmaterial.html

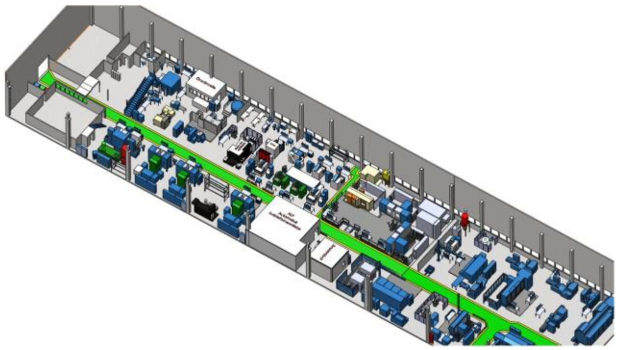

Figure 2. Example of a production line for airplane engine components

2 The factory as a System of Systems

Figure 3 shows a major part of the factory, some 25.000 m2 floor space, with tens of large machines and hundreds of smaller pieces of equipment. This diagram shows only the physical part of the factory, which is run by hundreds of people supported by many IT systems.

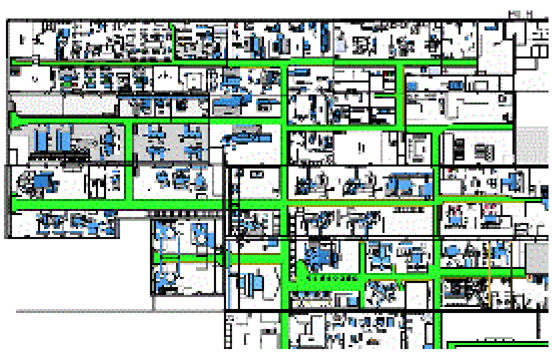

Figure 3. Top-level view of the (physical) factory.

Figure 4 makes an attempt at classifying the systems contributing to a production line. One category of systems is infrastructure, e.g. the buildings, utilities in the building, the storage and transportation infrastructure, the logistics infrastructure, which is a combination of humans and IT systems, and other information systems, especially the production tracking for quality assurance.

A production line makes use of many specific production machines for welding, drilling, and many more processing steps. Each machine uses a variation of tools (such as drilling bits) that have their own maintenance and operational flow. Storage, transportation, machining, and measuring require various fixtures. Throughout the production flow, many quality control operations take place in the form of machine-based measurements and visual inspections.

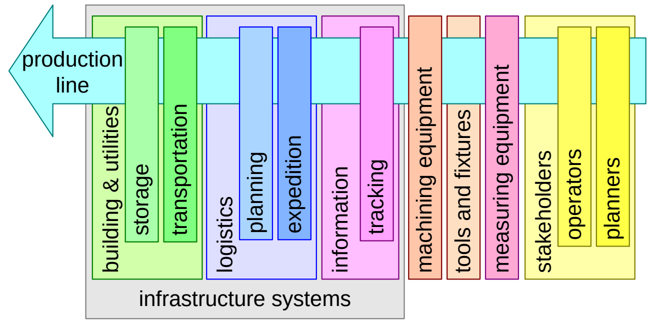

Figure 4. A single production line uses many infrastructure systems and specific systems.

A complication is that production lines make use of shared resources, especially the expensive machining equipment. An additional complication is that manufacturing space is limited; the total factory layout is a severely constrained puzzle. The flow production approach recommends a production line with products progressing in orderly fashion, from begin to end. However, the sharing of resources and space constraints result in production lines that are more scattered. Finally, products sometimes need the same machine several times in the production flow.

The next complication is the interplay of machines, humans, and IT systems. The manufacturing machines are complicated systems themselves, with robots handling tools with high precision, driven by automated programs. The IT systems deliver orders and programs to the machines. Operators determine the local schedule, supervise the machine operation, handle input and output of goods, tools, and fixtures, and cope with exceptions. A typical product goes through tens of such processing steps. Logistics supervisors and expeditors ensure the flow of products through the entire production line. We observe several levels of scheduling: The order system that schedules the demand, the storage system that anticipates production and pushes material into the production line, and local machines where various production lines come together and need the same resource. This scheduling works due to human intelligence, cooperation, and experience.

3 The LEAN perspective

The current way of working is dominated by the conventional paradigm: maximizing the utilization of capital intensive systems. However, the dominating priority of utilization in combination with the resource sharing between production lines, necessitates queues (=intermediate storage) before shared resources and increases cycle time (time from start of production until completion). From a Lean perspective, the production is not “flowing”, and intermediate storage is a form of waste. Typical key performance parameters that other manufacturers use, such as (intermediate) stock size and cycle time score poorly, due to the dominance of utilization.

With current popularity of LEAN manufacturing, and the obvious significant stock size and cycle time, the step to wondering about the potential of LEAN is small. The company formed a project group to explore LEAN improvement to a particular part of a production line (a subset of an entire production line for a single product; a part of a part of the factory). The project team consists of employees with varying viewpoints: logistics, operations, expedition, and engineering. The logistics, operations, and expedition viewpoints match with the scheduling levels that we described earlier. The engineering staff works at factory level, providing support to all production cells and lines. The industry master students are typically working in engineering during their study of systems engineering.

4 Reflections on the LEAN project

The project team started enthusiastic by understanding the production line, and identifying challenge areas. An example of a challenge area was the first storage area at the beginning of production. Storage, in anticipation of production, pushes raw material into the first storage area. However, since two different products are processed at this location, the order of raw material is relevant. Operators have easy access to one end of the storage, and tend to work "first-in-first-out". If the desired production order does not match the raw material, the operator may use an undesired production order. Such bottleneck can be tackled in many ways, for example, by providing easy access for the operator to more than one piece of raw material.

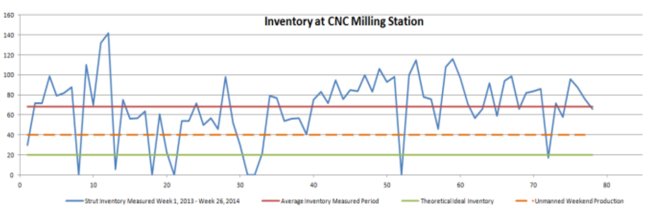

Figure 5. Actual amount of inventory at one of the processing stations

The project team also collected data, for example, the actual amount of inventory at one of the stations, as shown in Figure 5. The inventory before this station fluctuates significantly, and is much larger than the project team perceives as desirable. Despite the large inventory, the machine is starving incidentally, although very rarely.

Concurrently, Andersen modeled the same production line for the course. She discussed here models and findings with the project team. Figures 6, 7, and 8 show some of the about 20 models that she made during the course. Figure 6 shows a high-level workflow and the elaboration for the production of a single component. Figure 7 elaborates the component production with processing times and queues, while Figure 8 shows the same component workflow and the use of the resources (where Figure 8 still ignores the sharing of most of these resources).

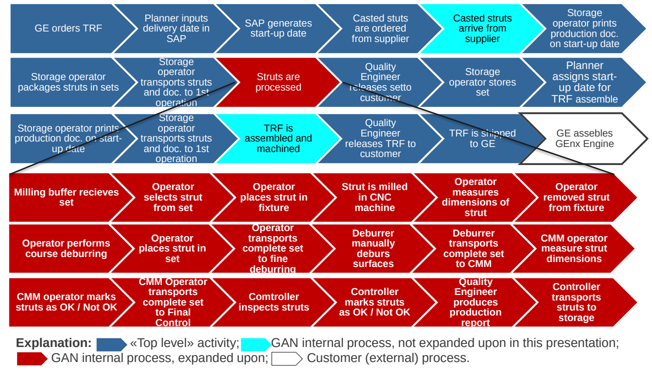

Figure 6. Example model of top-level and component-level workflow process

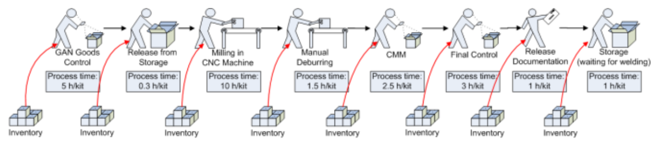

Figure 7. Processing times and intermediate stores for part of the production line

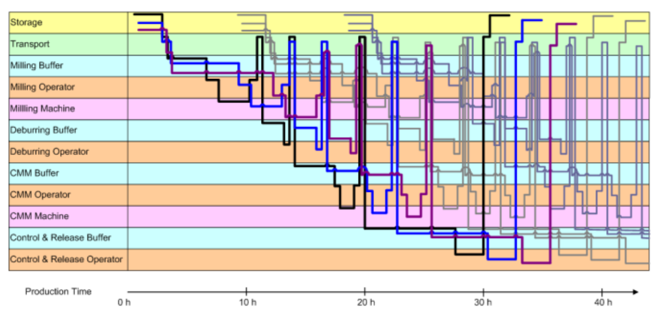

Figure 8. The component workflow in time with swimming lanes per resource

Although the LEAN approach applied tools as Value Stream Mapping, the project team was primarily tasked with implementing one of the many improvements identified, apply solutions to this problem and iterate in the hope to improve the entire production line. The modeling approach emphasizes modeling as means for understanding, reasoning, and communication. The modeling course advocates rapid iterations over multiple views and levels of details with the purpose of creating a shared understanding. The main idea is that gradually understanding is achieved at high, holistic level, as well as on more detailed level (since the devil is in the detail).

The modeling course asks among others things for a customer key driver graph (identify the key drivers and the relation to the key performance parameters of the system of interest), an integral cost model, a black box model of the system of interest, and a lifecycle model with sources of changes and their frequencies of occurrence. These models put the detailed models into perspective. The project team members did connect less, when models zoomed out further. The effect is that most project members reason and operate from a local, rather limited, understanding of the system. Local ideas are tried in the hope that they will prove to be beneficial. When students in the same course model systems in other domains, we observe similar phenomena. Engineers and other stakeholders "living" deep in the system, find it difficult to zoom out and to take an outward in perspective.

One of the concepts in Lean manufacturing is "tact": a regular heart beat that induces a smooth flow in production. This rhythm typically is not a single rigid value; rather the system should be able to cope with small variations to increase robustness (hence, be able to cope with deviations). The question is what the tact frequency should be. The tendency of the project team was to think in tact of hours, since processing operations may take hours. When zooming in on the processing itself, we see that currently the system lacks natural tact: processing times vary significantly, while resource sharing, combining multiple components in batches, and operator schedules (lunch, diner, and shifts) cause even more variation in flow speeds.

5 A top-down perspective

The modeling approach forces an iteration between bottom-up and top-down perspectives. The observations of the Lean efforts ask for a clarification of objectives. The current bottom-up approach assumes that a regular flow with near constant tact and minimal stocks is something to strive for. However, what are the ultimate drivers for the customer of the factory? Analysis results in the following key drivers for the direct customer of the factory (e.g. the airplane engine manufacturer):

- Delivery of components
  - In time
  - At proper quality
  - Sustainable over decades
  - Fully traceable
- Affordable cost level

The factory itself adds some business and local key drivers:

- Limited use of capital
- Fit in geographical and social constraints

From a top-down perspective, we need an understanding of how the factory will satisfy these key drivers, and what improvements are feasible to enhance performance in terms of these key drivers. In many manufacturing systems, the cost of stocks contributes significantly to the use of capital and the cost of production. Similarly, in many markets, the time to deliver to market is short. A short cycle time facilitates fast response to market conditions. In the airplane engine market we see time constants of years, and we see an equipment cost that is high. This combination asks for another approach than the fast-moving volume-production markets, like automotive and consumer goods.

6 Revisiting the System of systems perspective

What we observe in this case seems to be typical for system of systems: the focus of individuals and the organization is on constituting systems, e.g. the machines, tool, fixtures, storage, transport, logistics, expedition, and quality. However, the holistic viewpoint, integrating the constituting systems into a supersystem that performs as needed is poorly covered. We need specific attention and responsibility for the end-to-end manufacturing system. In this particular case, the end-to-end responsibility has to cover multiple production lines, due to the resource sharing between production lines.

Another complicating factor in System-of-systems is the variation of time-constants over the constituting systems and the various functions. Figure 9 shows an exponential time axis populated with the time constants of the frequency and response time of life cycle changes for the production line. For example, it shows that tools may wear down in one day, while replacement should take place within an hour. At the other end of the spectrum is the machine lifetime of decades and response can be anticipated a long time before replacement.

In a manufacturing environment most stakeholders have an operational perspective, which tends to create a short horizon. Operational problems are urgent and require quick resolution. Lindtjørn observed during his master project using A3 architecture overviews for a production line [8] "*The fast-paced nature of the production environment has proved to be an obstacle when attempting to get an overview.*"

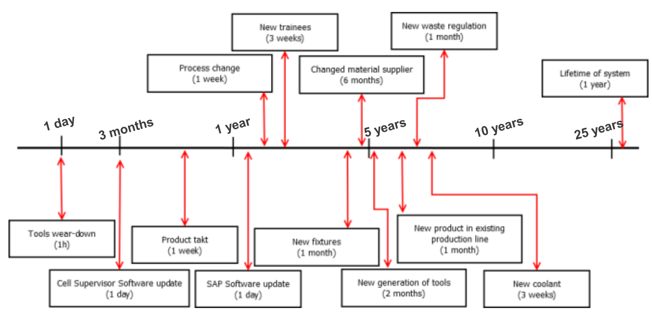

Figure 9. An exponential time axis populated with the time constants of the frequency and response time of life cycle changes.

Andersen developed Figure 9 as part of the modeling course. However, since the diagram was too abstract and didn't bring a direct message to the project team, it was not included in the final set of models for the course.

Some considerations for such system of systems to be made are how strategic and tactical perspectives can be organized, and especially who is capable of operating at higher abstraction levels and longer time scales.

7 Other Reflections on SoS

Since the factory is an Enterprise level SoS with clear mission and responsibilities, we expect a *Directed* or *Acknowledged* (see [9]) type of SoS. However, we clearly observe that the actual situation is closer to *Virtual* type of SoS. The consequence is that key performance parameters such as cycle time and amount of inventory, and the variation of these parameters emerge.

We advocate a transition to an *Acknowledged* type of SoS, by conceptual modeling at production line and factory level. Starting points for such conceptual modeling are the customer and factory key drivers (top-down) and concurrently a bottom-up empirical approach to understand today's emerging behavior of the key performance parameters. When these modeling efforts connect, then the SoS engineers have the means to transition from pure emergence to partially designed behavior and performance.

8 Conclusions

The aggregation of tens of physical systems, IT systems, and stakeholders into a factory with multiple production lines for components of airplane engines results in a system of system with all associated complexity. Modeling at the level of a single or a few systems helps engineers to communicate within the organization. However, a challenge is to lift modeling to the level that it supports strategy and tactics at higher abstraction levels and longer time scales.

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