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Modeling of manufacturing systems and analysis of their performances

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Abstract

Under the tendency of Industry 4.0, the Cyber-Physical System (CPS) is used to digitize and intelligent the supply, manufacturing and sales information in production, and finally realize fast, effective and personalized product supply. And the concept of ‘Digital Factory’, ‘Digital Production’ and ‘Digital Logistics’ were introduced. With the help of continuous development of automatic control and advanced sensor technology, Intelligent Manufacturing could be achieved. For this purpose, the modeling of the production line can be a good method for describing how the ‘Digital Factory’ works, as well as an achievable method for analyzing the performance of a production line under construction.

In this paper, we develop a hierarchical modeling for manufacturing system. Based on the IEC 62264 Standard and ISO 22400 Standard. During the developing we also refer to some existing models such as RAMI4.0. And we introduce a practical production line including two computer numerical control (CNC) machines. On which we apply the hierarchical modeling and test the performance of it.

Keywords: Industry 4.0; Digital Factory; Intelligent Manufacturing; hierarchical modeling; IEC 62264; RAMI4.0

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List of Acronyms

CIMOSA	Computer Integrated Manufacturing Open System Architecture
CNC	Computer Numerical Control
CPS	Cyber-Physical System
ERP	Enterprise resource planning
HVAC	Heating, ventilation, and air conditioning
KPIs	Key Performance Indicators
PERA	Purdue Enterprise Reference Architecture
RAMI4.0	Reference architecture model for Industry 4.0

1. Introduction

The concept of the Industry 4.0 is proposed by German in 2013 Hanover Industrial Expo. It aims to improve the intelligence level of the manufacturing industry, establish smart factories with adaptability, resource efficiency and genetic engineering, and integrate customers and business partners in business processes and value processes. Its technical foundation is the Information Communication Technology and the Cyber-Physical System.

In manufacturing area fully automatic manufacturing and digital management of manufacturing are achieved in many companies. Nowadays the advanced technology allows continuous interactions among the machines. To clearly describe the intelligent manufacturing systems, we develop such a hierarchical model. With the help of this model framework, we can also analysis the performances of these manufacturing systems.

1.1 Background of Industry 4.0

The so-called Industry 4.0 is a division based on different stages of industrial development. According to the consensus, Industry 1.0 is the era of steam engines, Industry 2.0 is the era of electrification, Industry 3.0 is the era of information technology, and Industry 4.0 is the era of using information technology to promote industrial transformation, that is, the era of intelligence.

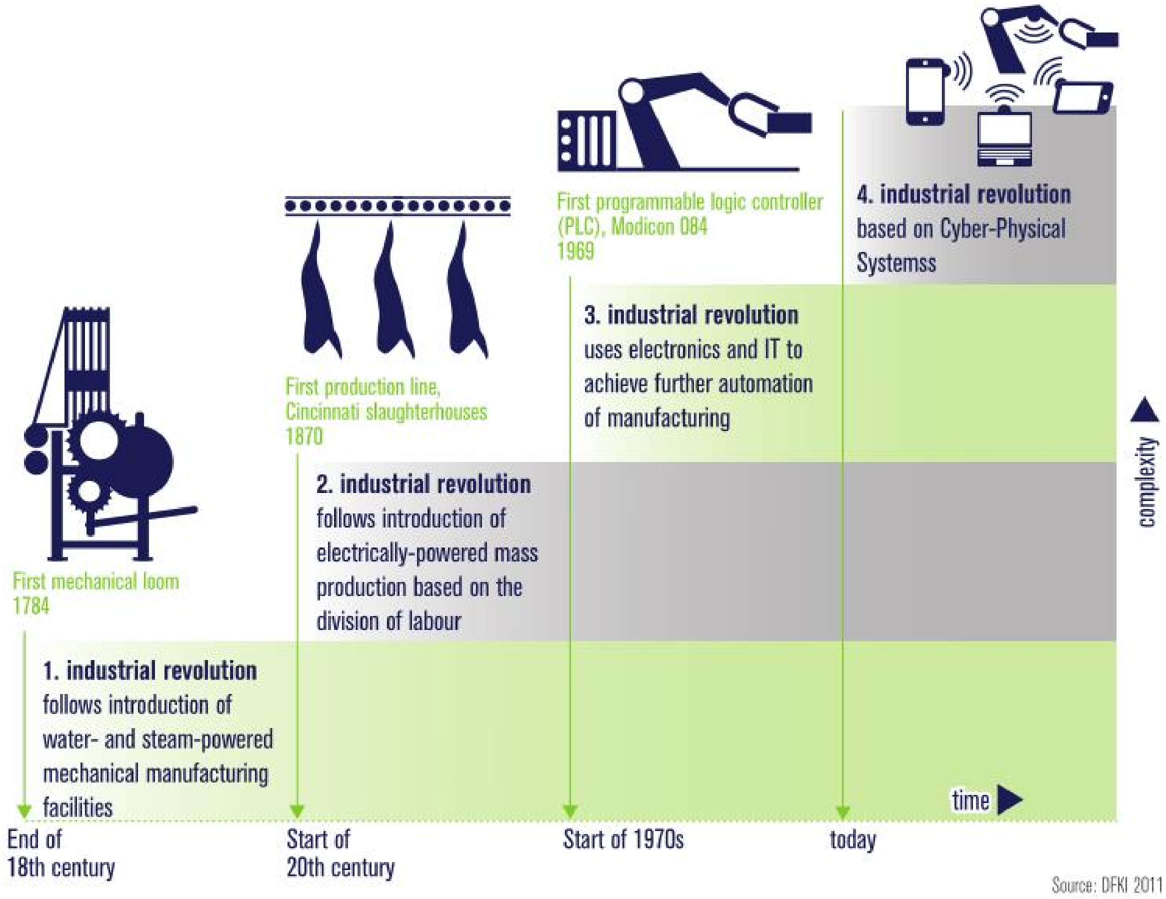

Figure 1.1 The four stages of the Industrial Revolution

The 1st industrial revolution refers to the technical revolution happened in 60s of 19th century in Britain. The steam engines increased the need for supplies of iron, steel and coal, which was met by a series of improvements in mining and metallurgy, and the development of the textile, mining and metallurgical industries created a need for improved means of transport. This phase united the world to a greater degree than it had earlier been in the Roman or Mongols; and made possible the European domination of the world, which lasted until The Industrial Revolution spread to other regions.

The 2nd industrial revolution happened in the 60s of 19th century among European, the US and Japan. It was also characterized by the development of mass-production technologies. Science and methods of mass production have influenced not only industry but agriculture as well. Towards the end of the nineteenth century, natural fertilizers gave way to purer forms of essential inorganic substances, and the worldwide production of inorganic substances greatly increased.

The 3rd industrial revolution started from the 1940s and 1950s, it is a major revolution in the field of science and technology that occurred after World War II. The utilization and development of space technology is a major achievement of this technological revolution. It has promoted major changes in the social and economic structure and the structure of social life. The third scientific and technological revolution has caused the proportion of the primary industry and the secondary industry in the national economy to decline, and the proportion of the tertiary industry has increased. In order to adapt to the development of science and technology, capitalist countries generally strengthen the state's support for scientific research, and greatly strengthen the support and capital investment in science and technology. With the continuous advancement of science and technology, major changes have also taken place in all aspects of human life, such as clothing, food, housing, transportation, and use.

Nowadays we are in the trend of 4th industrial revolution. The essence of Industry 4.0 is to use data flow automation technology to shift from economies of scale to economies of scope, and to build a heterogeneous and customized industry with homogeneous costs. For the reform of the industrial structure, this is a crucial role. The core feature is interconnection. Internet technology reduces the information asymmetry between production and sales, and accelerates the interconnection and feedback between the two. Therefore, a consumer-driven business model has emerged, and Industry 4.0 is the key link to realize this model. Industry 4.0 represents the intelligent production of "Internet + manufacturing", giving birth to a large number of new business models.

1.2 Hierarchical model

During the Industrial 4.0 era, the concept of ‘Digital Factory’ indicates the using of digital technology for modeling, communications and to operate the manufacturing process. To construct a ‘Digital Factory’ which could represent a practical manufacturing system, the ability of simulation is necessary. What we consider is a model that can describe the entity construction, the variables describing the system and the profitability and so on. In this paper we developed a hierarchical model framework with seven layers. Each layer describes a different level design of the manufacturing system. And such a modeling can be applied not only on an existing production line, but also on the production line that is still in the planning stage. The purpose of such modeling is simulating the performance of the production line. Help peoples understand better how the production line is, and design the management and the operation strategy of it. And finally make the production line more profitable and more environmentally friendly.

1.3 Structure of thesis

In chapter 1, industry 4.0 and the hierarchical model are briefly introduced.

In chapter 2, three types of manufacturing models are introduced, from which we get very useful references and suggestions for building the hierarchical model.

In chapter 3 (important part), we develop a seven-layers hierarchical model to describe the manufacturing systems. The relative important parameters of this model are the status variables, control variables and the financial variables. For each model layer we established a KPIs system for the performance evaluations.

In chapter 4 (important part), we summarize the model we developed and create queen model to describe it.

In chapter 5, we tried to apply our hierarchical model to a production system and describe the procedures of performance analysis.

In chapter 6, a conclusion that the modeling makes the manufacturing system easier to understand and control, and possibility to make it more profitable. The feasibility of this model should be verified by applying it on other more complicated manufacturing system.

2. Reference Models for Manufacturing Operation

Before we start the construction of our model, we studied some models established by other organizations or individual. This part includes our understandings of these models. They provide us useful rules and references for develop a hierarchical model.

2.1 Reference architecture model for Industry 4.0 (RAMI4.0)

RAMI 4.0 combines the crucial elements of Industry 4.0 in a three-dimensional layer model for the first time. Based on this framework, Industry 4.0 technologies can be classified and further developed.

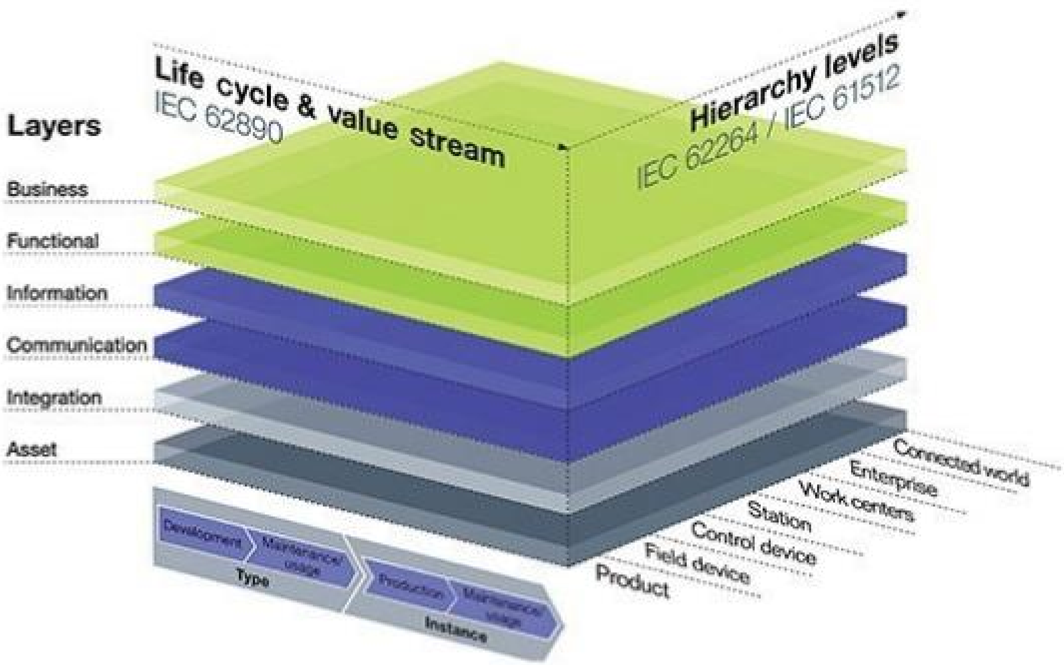

Figure 2.1 Reference architecture model for Industry 4.0 (RAMI4.0)

Within these three axes, all crucial aspects of Industry 4.0 can be mapped, allowing objects such as machines to be classified according to the model. Highly flexible Industry 4.0 concepts can thus be described and implemented using RAMI 4.0. The reference architectural model allows for step-by- step migration from the present into the world of Industry 4.0.

Following is the description of the three dimensions:

2.1.1 The “Hierarchy Levels” axis

Indicated on the right horizontal axis are hierarchy levels from IEC 62264, the international standards series for enterprise IT and control systems. These hierarchy levels represent the different functionalities within factories or facilities.

In order to represent the Industry 4.0 environment, these functionalities have been expanded to include work-pieces, labelled “Product”, and the connection to the Internet of Things and Services, labelled “Connected World”.

In this axis it introduced the different levels between which they are connected each other through the network. And they all communicate and interact across such a hierarchy level. Standardized by the international standards series for enterprise IT and control systems.

2.1.2 The “Life Cycle & Value Stream” axis

The left horizontal axis represents the life cycle of facilities and products, based on IEC 62890 for life-cycle management. Furthermore, a distinction is made between “types” and “instances”. A “type” becomes an “instance” when design and prototyping have been completed and the actual product is being manufactured.

In the “type” the manufacturer doing the modification or improvements of the products. In the “instance” once the product is delivered to the customer, the product’s information would be available to them. This axis connected the order planning, assembly, logistics, maintenance, customers. Make the whole system more flexible.

2.1.3 The “Layers” axis

The six layers on the vertical axis serve to describe the decomposition of a machine into its properties structured layer by layer, i.e., the virtual mapping of a machine. Such representations originate from information and communication technology, where properties of complex systems are commonly broken down into layers.

2.2 Computer Integrated Manufacturing Open System Architecture (CIMOSA)

CIMOSA, standing for "Computer Integrated Manufacturing Open System Architecture", is an enterprise modeling framework, which aims to support the enterprise integration of machines, computers and people. The framework is based on the system life cycle concept, and offers a modelling language, methodology and supporting technology to support these goals.

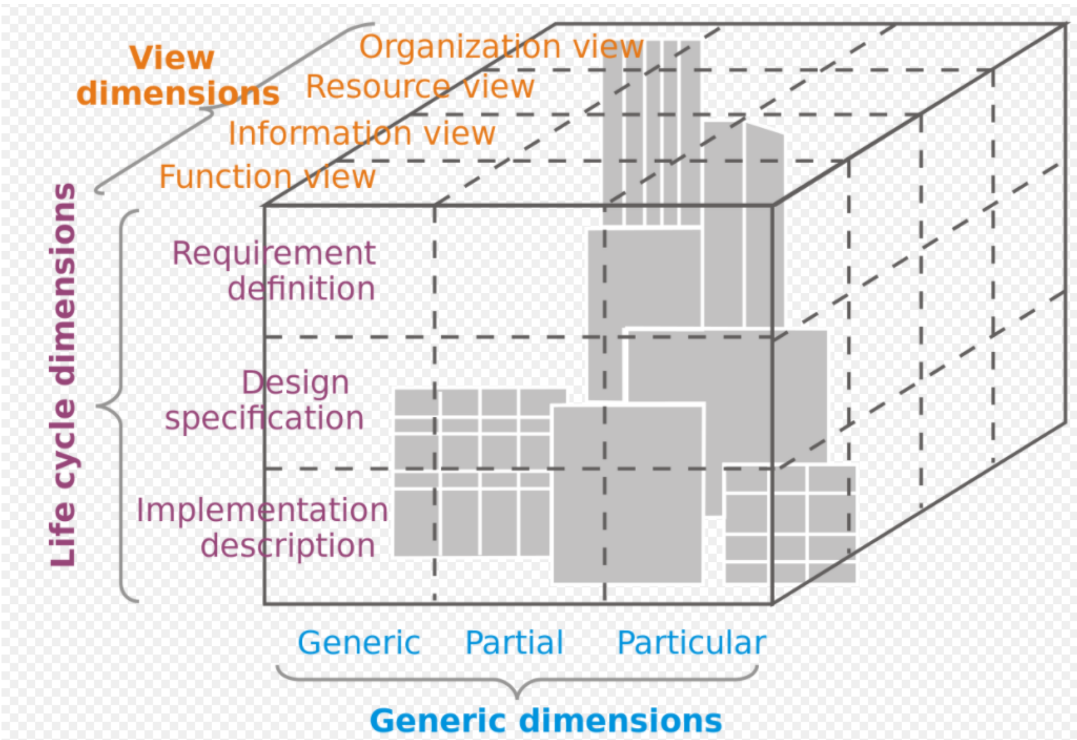

Figure 2.2 CIMOSA cube

The CIMOSA model framework is composed of three dimensions:

2.2.1 Generic dimensions

This dimension reflects the modeling process from generic framework to a specific enterprise. By starting from a generic framework, the cost could be reduced.

2.2.2 Life cycle dimensions

Here indicates the construction process of this model. Starting from defining the requirements, to how to design the specifications, finally ends with the description of the implementation.

For the specific enterprise the specific structure design is needed.

2.2.3 The view dimensions

The view dimensions mainly compose of 4 views. They are function view, information view, resource view and organization view. It supports the model to describe the enterprise from different perspectives. And it enables the collaboration of the modeling of different structures.

2.3 Purdue Enterprise Reference Architecture (PERA)

Purdue Enterprise Reference Architecture (PERA) is a 1990s reference model for enterprise architecture, developed by Theodore J. Williams and members of the Industry-Purdue University Consortium for Computer Integrated Manufacturing.

PERA can model the enterprise in multiple layers and in multiple stages of the architectural life cycle.

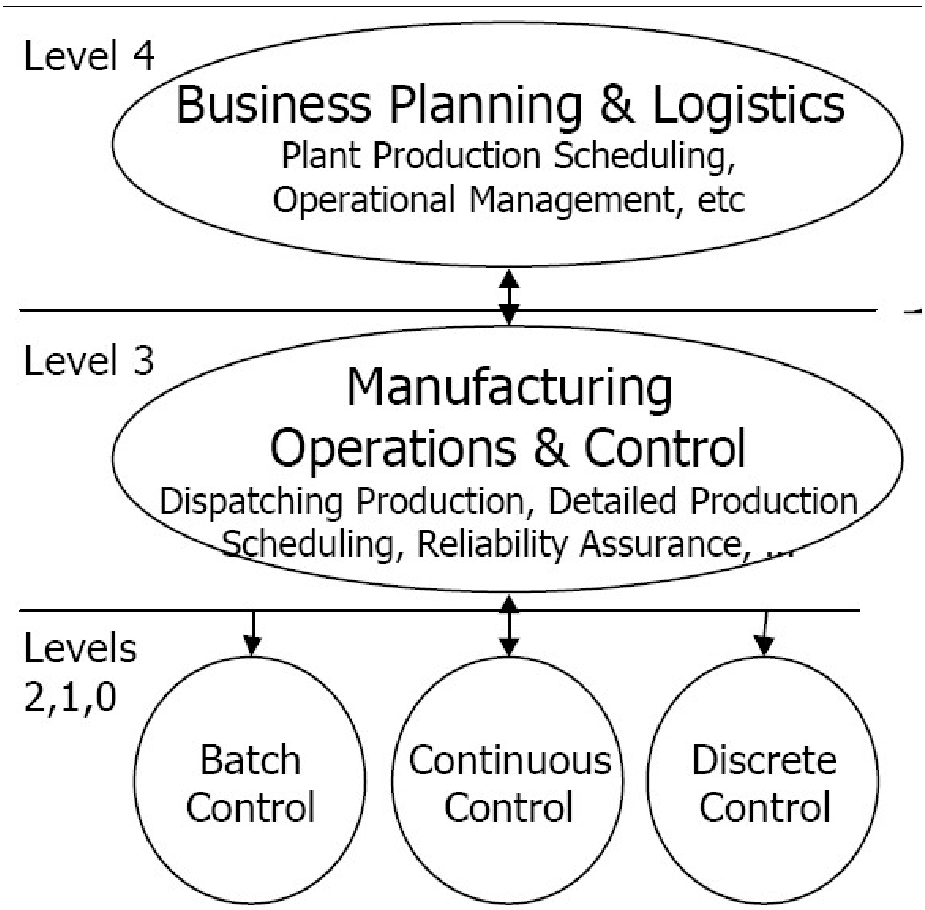

Figure 2.3 PERA Reference model

PERA Reference model mainly consists of 5 levels.

2.3.1 Level 4 Business logistics systems

Level 4 manages the business-related activities of the manufacturing operation. Enterprise resource planning (ERP) is the primary system; establishes the basic plant production schedule, material use, shipping and inventory levels. Time frame: months, weeks, days, shifts.

2.3.2 Level 3 Manufacturing operations systems

Level 3 manages production work flow to produce the desired products. Batch management; manufacturing execution/operations management systems (MES/MOMS); laboratory, maintenance and plant performance management systems; data historians and related middleware. Time frame: shifts, hours, minutes, seconds.

2.3.1 Level 2 Control systems

Level 2 consists the functions of supervising, monitoring and controlling the physical processes. Real-time controls and software; DCS, human-machine interface (HMI); supervisory control and data acquisition (SCADA) software.

2.3.1 Level 1 Intelligent devices

Level 1 senses and manipulates the physical processes. Process sensors, analyzers, actuators and related instrumentation.

2.3.1 Level 0 The physical process

Level 0 defines the actual physical processes.

3. Production Hierarchical Models

In Industry 4.0, to achieve the goal of building a smart factory, we focus on intelligent production system and process. Including production logistics management, human-computer interaction and the application of 3D technology in industrial production process i.e. A CPS makes the interaction between each physic part possible.

In our hierarchical model, the whole manufacturing system will be divided into7 layers. Layers will be interrelated each other. They are:

- Layout model layer: 2D representation of the manufacturing line in an assigned space
- 3D model layer: 3D representation of assets occupied space
- Plant service model layer: the input and output of materials and energy
- Status variables model layer: the variables describing the manufacturing system
- Control system model layer: managing the schedule of the production process
- Financial system model layer: costs and profits of the manufacturing system
- Social model layer: impact of the manufacturing system on society and environment

Considering about the details of each layer, we are focusing on developing a Key Performance Indicators (KPIs) system to evaluate different type of including variables. The variables refer to the status of elements, the geometric parameters, and also the relationship between variables and so on. Such variables will be transformed into numerical elements or one variable could consist of several elements, and being evaluated by the KPIs system. The results will be a reference for the performance of the manufacturing system. To evaluate the KPIs for the elements, we introduce a reference value as a perfect element. In this paper, the reference value is set upped after the studies on some technical articles and standards. Considering the exiting differences between the different manufacturing systems. We also provide a questionnaire for surveying a appropriate reference value for the specific need. That is, before applying this modeling procedure, setup the specific reference values for the systems is suggested. Here we introduce mainly the framework of the modeling, and provide the suggested values.

This model can be applied on mainly two cases.

First case is that the production line is still on a planning stage. Before practically building a factory as well as a production line. Build a virtual factory according to this hierarchical model could simulating the manufacturing system's performance with a relatively low cost. The modification and the scheduling of the factory can still be done before everything is fixed. We can forecast the costs, profits, the usage of materials and the influence on environment, and modify the plan easily.

Second case, after the production line start working, or we can directly build a model for a manufacturing system that already working. It will be a good method to monitor the operation of the system. For example, detecting the system error by reading the real-time status variables and compared it with the virtual one.

Besides if the manager plans to change the strategy of the system, he can simulate first on this model to get advice that the changes are better or worse. Thus reduce the risk of financial loss due to wrong strategy.

Following we introduce the details of each model layer.

3.1 Layout model

This layer represents the 2D layout of the manufacturing system.

Before designing the 2D layout, we should decide what product to be manufactured. How the production line work and the devices demand. Safety is also an important aspect to be concerned. Below are some rules should be followed:

● Reduce or eliminate waste and ensure a “lean” environment to minimize cost

- Simplify the manufacturing process, maximize effective use of equipment, minimize production lead times and delays. Design for preventive maintenance.

- Reduce moving and lifting costs. Reduce distances, Automate transportation modes if less expensive.

- Promote effective use of space and energy. Minimize floor area, use available cube space.

● Provide for employee convenience, safety, ergonomics, and comfort

- Availability of dies/tool

- Easy access to materials

- Avoid noise, set appropriate Heating, ventilation, and air conditioning (HVAC), lighting, moist and dust control systems

- Safety measures

● Support inventory control and minimization

● Avoid unnecessary investments that do not add value to the plant

● Promote effective use of people and productivity

In this model layer, we mainly consider the following variables:

Layout model variables	
Variable name	**Acronyms**
Total Aera	TA
Working Aera	WA
Raw Material Storage	RMS
Finished Products Warehouse	FPW
Maintenances Aera	MA
Service Aera	SA

Table 3.1.1 Layout model variables

3.1.1 Total Aera

The TA indicates the overall area of the plant, in which contain the manufacturing system. This parameter is a measurement data. And will be used in the subsequent computations of other variables.

3.1.2 Working Aera

The WA indicates the aeras occupied by the production system, such as the machines, conveyor belts and the robots. A plant may contain not only WA, different WA indicates the different production line function aera. In this part we introduce two elements for the KPIs evaluation.

First one is Floor space Utilization Rate (FUR). It refers to the ratio between Occupied Space Aera (OSA) and WA. In the working aera, not all the space is occupied by the devices and the necessary route, part of the space would be wasted. We consider that the higher the FUR, the better we use the space.

The FUR is ranked from 1 to 10. Rank 1 means the worst case, rank 10 the opposite. And in this paper, rank 1 refers to FUR equals to 50%, rank 10 refers to 95%. Every increasing of 5% means KPIs increase 1. The results are rounded according to the following table.

FUR KPIs evaluation										
FUR	50%	55%	60%	65%	70%	75%	80%	85%	90%	95%
KPIs	1	2	3	4	5	6	7	8	9	10

Table 3.1.2 FUR KPIs evaluation

The second element is the Surrounding Environmental Factors (SEF). It indicates the convenience for the devices. Such as the availability of the energy, gas, water and the raw material. The KPIs is ranked from 1 to 10. Rank 10 refers to the best case that everything needed is convenient to reach for the devices. Rank 1 is on the contrary. This element is linked to the variables included in the Plant service model in Chapter 3.3.

Working Aera Elements	
Element name	**Acronyms**
Floor space Utilization Rate	FUR
Occupied Space Aera	OSA
Surrounding Environmental Factors	SEF

Table 3.1.3 Working Aera Elements

3.1.3 Raw Material Storage

The RMS is the space that for storing the freshly received raw materials. And it is also the place for the trucks to unload the goods. The elements we consider important are the Capacity of Raw Material Storage (CRMS) and the Transport time between RMS and WA (TRW).

Element CRMS is the storage capacity of the raw material, we evaluate this element by calculating how many working days' usage of raw material can be stored. To evaluate this element, we need other elements in 3D model layer (Chapter 3.2), Plant service model layer (Chapter 3.3) and Status variable model layer (Chapter3.4). the evaluation will be done in the subsequent modeling procedures.

Element TRW is the time needed for transporting a packet of raw materials from the RMS aera to the WA. It can be an indication of the material flow efficiency. The quicker the raw materials can be transported; the more materials are available for the production devices in a specific time. TRW is ranked from 1 to 10. For the ranking procedure, we introduce a Reference TRW (RTRW) and an Actual TRW

(ATRW). The reference one it the time occurs in the ideal cases. and ATRW is the time consumed for a practical production line. The ratio between ATRW and RTRW presents the KPIs for TRW. The calculation can be done according to the following formula:

$$TRW = \frac{ATRW}{RTRW}$$

To calculate ATRW, other two elements are necessary. They are the Distance between RMS and WA (DRW), and Speed of the Transport device (ST). The device using for transportation could be a forklift, an automatic robot and a worker, depends on the different situations. ATRW is the ratio between DRW and ST:

$$RTRW = \frac{DRW}{ST}$$

While RTRW is related to the DRW and ST, but it is calculated under an ideal situation. Without any disturbances on the transporting process or delays of the transport devices. Normally ATRW should be lager than RTRW, the definition of KPIs for TRW is:

TRW KPIs evaluation										
TRW	5	3	2.75	2.5	2.25	2	1.75	1.5	1.25	1
KPIs	1	2	3	4	5	6	7	8	9	10

Table 3.1.4 TRW KPIs evaluation

The TRW result is rounded depending on closeness to the value in the table. For example, if TRW is 1.2, it is closer to 1.25, then the KPIs would be rank 9. ATRW is an average value for a certain WA. In case we have more than one WA, the evaluation should be done for each single WA. Depending on the importance of each WA, calculating a weighted average TRW KPIs for the whole system. In our table we consider the worst case is that transporting time consumed is five times of the RTRW, the blocking of the system may happen. The TRW scales values could be adjusted or modified to make it more suitable for any specific manufacturing system.

Raw Material Storage Elements	
Element name	**Acronyms**
Capacity of Raw Material Storage	CRMS
Transport time between RMS and WA	TRW
Reference TRW	RTRW
Actual TRW	ATRW
Distance between RMS and WA	DRW
Speed of the Transport device	ST

Table 3.1.5 Raw Material Storage Elements

3.1.4 Finished Products Warehouse

The FPW is the warehouse for storing the finished products. And it is also the output point of the manufacturing system. Familiar with the elements in the RMS part, the Capacity of FPW (CFPW) should be concerned. Besides also the Transport time between WA and FPW (TWF) is an important element to be evaluated.

CFPW KPIs evaluation will be introduced in the subsequent chapters. With the height element in Chapter 3.2 and other flow variables and processing variables in Chapter 3.3 and Chapter 3.4.

Element TWF is the time for transporting a finished product from WA to the FPW, it defines how efficiency the finished products could be removed from WA, thus the performance to avoid the production process blocking. Beside of this, a larger flow capability allows the possibility to produce more products. For the TWF KPIs evaluation we introduce again a Reference TWF (RTWF) and an Actual TWF (ATWF). RTWF is the time needed to transport the finished products in ideal case. ATWF is calculated by other two practical elements, Distance between WA and TWF (DWT) and ST.

$$TWF = \frac{ATWF}{RTWF}$$

$$RTWF = \frac{DWT}{ST}$$

TWF KPIs is ranked from 1 to 10. RTWF is calculated according to the DWT and the ideal speed of the devices. And ATWF is measured form a practical manufacturing system. We provide the following table for TWF KPSs evaluation:

TWF KPIs evaluation										
TWF	5	3	2.75	2.5	2.25	2	1.75	1.5	1.25	1
KPIs	1	2	3	4	5	6	7	8	9	10

Table 3.1.6 TWF KPIs evaluation

Generally, ATWF should be lager than RTWF. And the ratio between them refers to the performance of the transporting system of finished products. If TWF is equal to one, that means the production system is working in a perfect situation. Usually, it can be one because of many uncertainties. But its value could be close to one. The final result value is rounded depending on to which value scale in the table the calculated result is closer. For example, if the result is 2.9. the corresponding KPIs is rank 2. The gap between rank 1 and rank 2 is relatively large, in that range the transporting system probably doesn't work well. Maybe because of the production line blocking, or the FPW is full and can not receive anymore products. That would be a very bad situation. We don't have to accurately evaluate the number; it is necessary to repair the system or change the production strategy.

Also, in this part the TWF scales in the table are suggested values, for any specific need they can be changed.

Finished Products Warehouse Elements	
Element name	**Acronyms**
Capacity of Finished Products Warehouse	CFPW
Transport time between WA and FPW	TWF
Reference TWF	RTWF
Actual TWF	ATWF
Distance WA and TWF	DWT
Speed of the Transport device	ST

Table 3.1.7 Finished Products Warehouse Elements

3.1.5 Maintenance Aera

The function of MA in the plant is maintain the production tooling. For a long-time equipment's usage. The maintenance is an effective method to extend the lifecycle of tools and equipment. Generally sizing the maintenance room is dependent on the designer's desire. In this paper we consider the maintenance aera influences the performance of the manufacturing systems. And we develop a KPIs evaluation rule for it.

By comparing the Actual MA (AMA) to a Reference MA (RMA) and calculating the ratio between them, the maintenance capability could be scaled into a 10 levels rank. AMA indicates the actual place occupation of the MA in the plant. RMA is a reference aera calculated according to the rules we will introduce bellow.

Considering about RMA, we introduce several elements for the calculations. Here we take reference to a Textbook named 'Manufacturing Facilities Design & Material Handling'. For every maintenance people we should provide them with about 37 square meters of space each. And the maintenance people we need typically accounts for 3 percent of the Total Plant Personnel (TPP). The value of element TPP we will define the calculation later in the Chapter 3.4 and Chapter 3.5. as a result, we calculate RMA according to the formular bellow:

$$RMA = Roundup(TPP * 3\%) * 37$$

Obviously we round up the number of maintenance people, and the result is a recommend MA for the plant. While for some special plant the MA could be particulate, the RMA should be recalculated for that case.

Then the elements AMA and RMA will be helpful to evaluate the performance of maintenance.

$$MA = (1 - \frac{|AMA - RMA|}{RMA}) * 10$$

MA KPIs evaluation										
MA	1	2	3	4	5	6	7	8	9	10
KPIs	1	2	3	4	5	6	7	8	9	10

Table 3.1.8 MA KPIs evaluation

We try to calculate the closeness between AMA and RMA, the less difference between each other of them, the better the maintenance performance. The result of MA is not always an integer, we define its KPIs by comparing to which MA scale in the table the result is closer. In the KPIs evaluation MA is divided into ten levels. Level 10 refers to a perfect MA in the plant, a small MA may not satisfy the demands, however a too big MA also leads to the waste of spaces as well as energies. We could notice that a low level of MA KPIs does not means that the plant is completely not good. MA KPIs only indicates the maintenance performance in a specific plant. But as we just discussed, the maintenance service can be contracted out, partially or totally.

Maintenance Aera Elements	
Element name	**Acronyms**
Actual Maintenance Aera	AMA
Reference Maintenance Aera	RMA
Total Plant Personnel	TPP

Table 3.1.9 Maintenance Aera Elements

3.1.6 Service Aera

SA in this paper represents the aeras contain the facilities such as Locker rooms, Toilets and Break aeras. In support of the employee needs and requirements.

In this part we will discuss about the space requirement for such facilities. In general, there are many types of employee needs, here we consider only those necessary or relatively important ones inside the plant. They are Locker rooms, Toilets and restrooms, medical facilities and offices (system control room). Almost the place requirements of these aeras are related to an element Actual Plant Personnel (APP), this element is different from TPP we introduced in Chapter 3.1. 8.. Nowadays more and more automatic production machines present. The needs of worker decreases, APP indicates only the real number of personnel in plant. While TPP is an element associated with the working hour for the production. For an automatic production line, we may need less employees with respond to a traditional one. The calculation of APP will be introduced in the Chapter 3.4.

According to the present textbook. We setup the place requirements as following:

Service place requirements	
Facility name	**Requirement[m*m]**
Locker room	0.37/employee
Toilets and restroom	8/20 employees
Medical facilities	4(first-aid rooms) 35(medical facilities) /50 employees
Offices	20/employee

Table 3.1.10 Service place requirements

Referring to the requirements above, we calculate a Reference Service Aera (RSA). And the element Actual Service Aera (ASA) can be measured from a real plant to which is going to be modelling.

While the plant is relatively small, the APP less than 200:

$$RSA = (0.37 + 20) * APP + 8 * Roundup\left(\frac{APP}{20}\right) + 4$$

While APP is lager than 200:

$$RSA = (0.37 + 20) * APP + 8 * Roundup\left(\frac{APP}{20}\right) + 35 * Roundup(\frac{APP}{50})$$

The ratio between ASA and RSA represents the degree of satisfaction of needs.

$$SA = \frac{ASA}{RSA} * 10$$

SA KPIs evaluation										
SA	5.5	6	6.5	7	7.5	8	8.5	9	9.5	10
KPIs	1	2	3	4	5	6	7	8	9	10

Table 3.1.11 SA KPIs evaluation

As described in the table, the range of SA is from 55% to 100%. In the case when SA ratio lower than 55%, we consider it as a worst case, the KPIs refers to rank 1. The necessary employee's needs can not be satisfied. Rank 10 KPIs refers to a very good case that almost all the employee's needs can be satisfied. In some situation the ratio may exceed 100%, that means the plant owner is willing to provide his employees a wonderful working environment.

Service Aera Elements	
Element name	**Acronyms**
Actual Service Aera	ASA
Reference Service Aera	RSA
Actual Plant Personnel	APP

Table 3.1.12 Maintenance Aera Elements

3.2 3D model

3D model, which is based on last 2D model layer, indicates the space occupancy of the system. Basing on the XY dimension from 2D model, adding information about the workshop height to depict the spatial layout. The height parameters provide us an indicator to design other auxiliaries in the plant like HVAC, lightning systems. Probably in a plant there will be the second floor or even the third floor for the offices and other employees' services aeras. But usually, the storage aera and the warehouse have a similar height as the building. And the overhead travelling crane in the plant is needed for moving the heavy devices.

In our approach, we focus on the variables that have a strong relationship with the production process. To calculate the capacity of Raw Material Storage and Finished Products Warehouse. We need another variable named Height of Plant (HP). Multiply HP and the RMS aera or FPW aera we get their space occupations respectively. Such spaces contain the shelves or boxes for storing raw material or finished products. However, the capacity of these spaces is dependent on the material flow rate and the production rate. The calculations and the performance analysis will be done in Chapter 3.4, after we introduce other status variables of the production devices and the logistic systems.

3D model variables	
Variable name	**Acronyms**
Height of Plant	HP

Table 3.2.1 3D model variables

3.3 Plant service model

This model layer includes various kinds of plant service facilities. One part is the facilities to satisfy the employees' needs and requirements. We have a brief introduction of them in Chapter 3.1.9. we analyzed the performance of SA by considering only the floor space occupations of some important facilities. Actually, there are mane other facilities could be concerned. Such as the entrance of employees, the cafeteria and the lunchrooms etc. Besides also the facility quality influences the employees' feel. But in our approach, we do not discuss the details of such facilities. We spend more focus on that flow variables that influence the production line working process.

First the plant services we consider important are the Raw Materials Unloading Rate (RMUR) and the Finished Product Manufacturing Rate (FPMR). They represent the goods flow of input and output of our plant respectively. And these two rates will determine the capacities of RMS and FPW. However, to calculate RMUR and FRMR we still need more variables that represent the processing systems status, with those variables we know how many raw materials we need in a certain time interval, as well as how fast our machines can produce the goods. Also the variables in Chapter 3.5 are needed for the calculation and evaluation. In the control system model, we will have the information of the production strategies and the production scheduling. They determine what we are planning to produce and how many we need.

Secondly, the Electrical Power Supply (EPS), Plumbing Systems (PS) and Compressed Air Systems (CAS) are crucial energies services of a good plant. Each of them has multiple usages in the plant. We set them as the variables in the Plant service model.

Plant service model variables	
Variable name	**Acronyms**
Raw Materials Unloading Rate	RMUR
Finished Product Manufacturing Rate	FPMR
Electrical Power Supply	EPS
Plumbing Systems	PS
Compressed Air Systems	CAS

Table 3.3.1 Plant service model variables

3.3.1 Raw Materials Unloading Rate

RMUR is the rate represents how fast the raw materials are importing into the RMS aera. Usually, we need an RMS large enough to storing the raw materials for the production lines to consume at least 15 days. This value of 15 days is a technical data comes from a textbook. It can not always be the best value for RMS design, specific plant may have a specific need. Here we just provide a recommend data. It is a variable depends on the plant designer.

As for the evaluation of RMUR, we provide another variable Raw Materials Consuming Rate (RMCR), RMCR and the 15-days determine the capacity of RMS. And RMCR is a result coming from production processing. The variables in Chapter 3.4 are necessary to the calculation of RMCR. In this chapter we evaluate the performance of RMUR by comparing it with RMCR. The situation that when RMUR is equal to RMCR, means that the raw materials handling is in a relative balance condition. And it is a reference condition in our approach. As for the definition of RMCR and RMUR, we take the average value of them for 30 work days. It includes as least 2 cycles of raw materials consuming. To evaluate performance of the Flow of RMS (FRMS), we compute the ratio between RMCR and RMUR.

$$FRMS = \frac{RMCR}{RMUR}$$

FRMS KPIs evaluation										
FRMS	1.5	0.8	1.4	0.85	1.3	0.9	1.2	0.95	1.1	1
KPIs	1	2	3	4	5	6	7	8	9	10

Table 3.3.2 FRMS KPIs evaluation

As we discussed above, the ideal situation is that RMCR and RMUR are in a balance condition. So, when FRMS equals to 1, the raw material consuming and importing is under a most stable condition. It represents the highest level of FRMS KPIs, rank 10. It is not good that RMCR is too much lager neither too much less than RMUR. If RMCR is lager, it means that our raw materials supply does not meet the demand of raw materials consuming. At least for 30 work days interval. The larger the supply gap, the more difficult for the plant to recovery the production in the further days. We have an RMS for 15-days usage, when the FRMS is 1.5, we will consume all the storages in 30 work days. And if the plant does not increase the purchasing of raw material, part of the production system will stop working because of lacking of raw materials. The gap we consider in the KPIs evaluation becomes less when RMCR is less than RMUR. Comparing this situation with the opposite one, it is relatively not such serious. Once the FRMS KPSs is lower than 1. It indicates that the plant has purchased too much raw materials. The worst case in the KPSs table, represents that for a boundary condition that at the beginning of the production, the plant RMS is empty and the plant may purchase more raw materials. When FRMS is 0.8, the RMS would be full from a complete empty condition in 75 work days. Its function is to alert the owner that the check of the storage capacity is needed, and if necessary, the order scheduling or the raw materials purchasing activity should be changed.

Raw Materials Unloading Rate Elements	
Element name	**Acronyms**
Raw Materials Consuming Rate	RMCR
Flow of RMS	FRMS

Table 3.3.3 Raw Materials Unloading Rate Elements

3.3.2 Finished Product Manufacturing Rate

FPMR represents the total amounts of finished goods that the production line could produce per work day. To make this variable more representative and reasonable, we select it as an average number of the 15 days' amount output of finished goods. Because of the uncertainty of the order scheduling or other reasons. The output of each day may vary. The average rate could be a relatively stable variable to use in our model. In case the manufacturing system produces more than one product. The FPMR should be calculated for each product.

FPMR is a necessary variable to evaluate the CFPW. Again, according to the technical data in the text book, the Capacity of FPW should be at least large enough to store 15 days finished goods outputs of the system. The warehouse storage could be flexible that if one of the finished goods amounts exceeds its storage capacity, while another finished good does not filled all its storage space. Temporarily the manager can share their storage spaces. However, when we design the FPW, we still need its capacity is enough for 15 days storage for each product.

FPMR is closely related to the variables in Chapter 3.4 and Chapter 3.5. The order defines how much products the system is going to produce, and the processing time of each machine determine how quick it could produce the product. Besides there are many other variables may influence FPMR. Combine all of these we get the result of FPMR. Once we get FPMR, the CFPW could be easily calculated.

In this part we develop a KPIs system to evaluate the performance of Flow of FPW (FFPW). To see if the FPW is capable to satisfy the storage needs of the relate manufacturing systems. Here we introduce a logistic variable Finished Produce Load Rate (FPLR). FPLR is a variable shows that how many goods are loaded to the trucks in the FPW aera and being transported outside of the factory. FFPW is calculated according to the subsequent formular:

$$FFPW = \frac{FPLR}{FPMR}$$

FFPW KPIs evaluation										
FFPW	1.5	0.8	1.4	0.85	1.3	0.9	1.2	0.95	1.1	1
KPIs	1	2	3	4	5	6	7	8	9	10

Table 3.3.4 FFPW KPIs evaluation

Also, all these three variables are average number for every work day of their 15 days amounts. While FPLR is equal to FPMR, FFPW is 1. We consider the outputs of this manufacturing system is in a balance condition. That means all of the produced goods are sold in a 15 days time interval. The finished goods are enough to complete the order and the production lines do not produce too many goods which the FPW can not fit. This condition is a relatively ideal condition. In real cases FFPW may hardly be 1, probably for a longer time interval FFPW may reach close to 1. In our KPIs evaluation, the case turns worse either FPLR is larger or smaller than FPMR. When FPLR is larger, it means that for that period the finished goods may be not enough to meet the orders requirements. The larger the deference, the worse the case. The worst case will occur then FPLR is 1.5 times FPMR. It predicts that a full FPW can keep the supply for at most 30 days. If the manager does not change any production operation strategy nor order schedule. They might face a cut off of the finished goods supplement. on the contrary, if FPLR is smaller than FPMR, it means that the production line makes too many goods than needed. At the beginning of the factory start, usually it happens because the factory probably produces more goods than the order requirements for some unexpected orders. In our KPIs evaluation the worst case is FFPW equals to 0.8. the result is a completely empty FPW will be full after 75 days if the producing operation does not be changed. Generally speaking, this is a situation not so sever, but a further changes of manufacturing plan or order schedule are recommended.

Raw Materials Unloading Rate Elements	
Element name	**Acronyms**
Finished Produce Load Rate	FPLR
Flow of FPW	FFPW

Table 3.3.5 Finished Product Manufacturing Rate Elements

3.3.3 Electrical Power Supply

In a modern factory electricity is an essential energy. The main function of an electrical service in a factory are Lighting, Power electrical engines and Power machines. The power electrical includes the material handing equipment, electrical machines. Nowadays Computerized Numerical Control machines (CNC machines) are widely used in the automatic production lines. As for power machines, for example furnaces and heaters are probably needed in a specific factory.

Normally the power supply can be divided into three types. High voltage (HV), Medium voltage (MV) and Low voltage (LV). A common value is shown in the following table:

Common Power Supply	
HV	220,150, or 132kV, for power > 5MW
MV	30, 20, 15, 10, 6, 5,3 kV, for power up to 4-5 MW
LV	380- 220 V, for power up to 100kW

Table 3.3.6 Common Power Supply

During designing stage, the designer should consider the type of distribution grid and distribution voltages. The distribution to points of use for different installed power load. Energy consumption at any point if use and distribution distances. Here are some possible types of power loads: machines for cold manufacturing, electrical welders, pumps, compressors, lighting and other non-manufacturing points of use. In this part we list an approximate power intensity for different type of industry. The data are collected from Textbook ‘Manufacturing Facilities Design & Material Handling’.

Approximate Power Intensity	
Type of industry	**W/m^2**
Chemical plants	250-500
Metal foundries	250-400
Sugar refineries	110-130
Paper mills	90-110
Mechanical works	80-100
Vehicle assembly lines	60-80

Table 3.3.7 Approximate Power Intensity

3.3.4 Plumbing Systems

Plumbing systems are also one of the most essential plant services. There are mainly three types of usage. Industrial water, drinking water and fire protection water. The industrial water supply can be used for the subsequent period:

- Cooling system
- Raw material
- Cleaning solvent
- Mechanical agent in hydraulic machines
- Steam production and heat transportation
- Dust and fumes cleaning

The water supply source is also a factor to consider. Usually, the sources can be public water through waterworks utility systems, surface water (river, lake or fresh water wetland) through pumps, and ground water through water wells. While designing looking for diversified sources to minimize supply risk is recommended. For water storage the water basins are needed. It insures the water accumulation to steady supply. The elevation of water basins is important to insure distribution capacity.

Inside the plant to make the water reachable to the facilities and devices. A proper water distribution network is necessary. Such a network should ensure the supply flexibility, which makes the systems adjustable. And the load capacity should be large enough for the facilities.

3.3.5 Compressed Air Systems

Compressed air is the second largest power energy after electricity, and it is also a process gas source with multiple uses. Its application range covers petroleum, chemical industry, metallurgy, electric power, machinery, light industry, textile, automobile manufacturing, electronics, food, medicine, biochemistry, national defense, scientific research and other industries and departments. Compressed air is an important power source. Compared with other energy sources, it has the following obvious characteristics: clear and transparent, easy to transport, no special harmful properties, no risk of fire, not afraid of overload, can work in many unfavorable environments, air is everywhere on the ground, whichever Endless.

Compressed air is produced via compressors, and it is better to use little number of large compressors than large number of small ones. It is largely used in most manufacturing facilities, for example in Europe 10% of all electricity used by industry is used to produce compressed air.

A good Compressed Air System consist of three main components.

● Compressors. Usually, positive displacement compressors and dynamic compressors are widely used. The compressors are equipped with soundproof enclosure. Beside intake systems for cool, dust-free, and dry air inlet are needed.

● Cooling water circuit. This system is necessary to remove the heat of compressors. By circulating cold water to cylinder heads, inter-coolers and after-coolers. The resulting warm water will be cooled in a cooling tower and circulated back to the compressors. The cooling performance depends upon the effectiveness of intercoolers, after coolers, which in turn are dependent on cooling water flow and temperature.

● Buffer tank. The functions of buffer tank include steady the compressed air supply, allow for compressors switch-offs and separate condensing. Its size should be design as approximately 10% of compressor capacity per minute.

3.4 Status variables model

In this Status variables model layer, we are focusing on the variables corresponding to the processing devices, and the facilities for material handling and inventory. These variables are taken from ISO 22400-2. Certainly, the designer or the manager of a manufacturing system should consider all the variables described in the standard. While in our approach we only discuss part of them in details. As which we consider them more important. As well as they are going to be elements needed during our performance evaluations in other model layers. The types of variables used in this part are mainly Time variables related to the workers and to the processing machines.

Bellowing we introduce the variables we pay more attention on:

● Actual Personnel Work Time (APWT), Actual Personnel Attendance Time (APAT).

APWT is the time a worker truly spent on the work on the production orders, the time for company authorized break periods are not included. While APAT represents the time interval between the start and the end of works for the workers. It is a combination of APWT and the break time during work. In one case that the majority part of the production devices is automatic. The workers are probably rarely needed on site. The evaluation of the workers' efficiency will be done with the time variables of the work units.

● Actual Unit Busy Time (AUBT)

AUBT it the actual time that a work unit is used for the production after it receives an order.

● Planned Run Time per Item (PRI)

PRI indicates the planned time for producing one quantity unit.

● Actual Production Time (APT)

APT is the actual time that a work unit is producing. It does not include the work unit set up time neither the unit down time. Moreover, the unit delay time is not considered neither. It is a variable shows the value-adding period of the work unit.

● Planned Busy Time (PBT)

PBT is the planned period available for the work unit to work on production orders. It is the result of planned operation time minus planned down time. The planned down time can be used for planned maintenance work.

● Produced Quantity (PQ)

PQ is the quantity of all goods that a work unit has produced in relation to a production order.

● Good Quantity (GQ)

GQ is the amounts of finished goods which meets the quality requirements.

● Actual Unit Processing Time (AUPT)

AUPT shall be the APT plus the actual unit setup time. The actual unit delay time is not included here.

Status model variables	
Variable name	**Acronyms**
Actual Personnel Work Time	APWT
Actual Personnel Attendance Time	APAT
Actual Unit Busy Time	AUBT
Planned Run Time per Item	PRI
Actual Production Time	APT
Planned Busy Time	PBT
Produced Quantity	PQ
Good Quantity	GQ
Actual Unit Processing Time	AUPT

Table 3.4.1 Status model variables

With the variables we introduced above. We are going to analysis the performances variables. By means of evaluating the efficiency of the workers and work units. these efficiencies may help us know more about the production system's capability. While part of them has a relation of other variables or performance evaluations in other model layers. The performance evaluations are done by considering the following variables in Table 3.4.2:

Status model performance indicators	
Indicator name	**Acronyms**
Worker Efficiency	WE
Allocation Efficiency	AE
Utilization Efficiency	UE
Availability	_
Effectiveness	_
Quality Ratio	QR
Overall Equipment Effectiveness index	OEE index
Net Equipment Effectiveness index	NEE index

Table 3.4.2 Status model performance indicators

3.4.1 Worker Efficiency

The worker efficiency considers the relationship between APWT and APAT. It can be calculated as the ratio of these two variables following the formula:

$$WE = \frac{APWT}{APAT}$$

The measure unit of WE are percent. It shows how much time a worker spent working on the production orders, during his attendance time. For example, in a work day one worker attends 9 hours, while he spent 1.5 hours on lunching and breaking. At that day his WE will be 83%. The higher the WE, the better. But in the same time the right of workers should be ensured. In practical cases a worker may work on several work units or production orders simultaneously, the calculation should involve all his activities.

The WE probably have a different level for different type of workers. In a traditional plant workers constitute a majority part of the manufacturing system. While for an automatic production lines, the needs of worker on site decreases. Their functions are substituted by the automatic robots. They need only a relatively small number of workers for controlling the system and maintenance them. The representative of WE will decrease. Instead, we can evaluate the efficiency of various automatic robots and manufacturing machines.

3.4.2 Allocation Efficiency

The AE is the ratio between AUBT and PBT. The difference exists because of the actual unit down time. Practically the work unit is hard to work 100 percent as planned. This variable describes in time scale how much the work unit complete scheduled tasks. Usually during planning stage, the designer may plan a reasonable more working time for flexibility, to avoid being influenced by the unexpected situations.

$$AE = \frac{AUBT}{PBT}$$

As for the unit of AE, it is represented by percent. The higher the result, the better. When the AE reaches high value, it means that the work unit can well fulfill the plan. While if AE reached a very low percent, the work unit probably are idle for a large part of its working time. The production may spend much more time to execute the order compared with the planned order execute time. It means an increasement of cost, and the manager should make decisions to avoid this situation.

3.4.3 Utilization Efficiency

The UE is the ratio between APT and AUBT. Considering the time for unit setup and the unit delay time. The time a work unit can process is only part of its busy time. Before the start of process, the work unit needs time to be prepared for the order. The time consumed is actual unit setup time. And in practice, the work unit may be delayed because of malfunction-caused interruptions, minor stoppages and other unexpected situations that leads to unwanted extension of the order processing time.

$$UE = \frac{APT}{AUBT}$$

The UE is measured by the unit percent. The higher the value, the higher efficient the work unit is. A large value of UE is expected. It is almost impossible to reach 100 percent because of the existing of unit setup time. During production the manager should minimize the unit setup time. If the UE is on a very low stage. There should be some issues related to the order scheduling or the work units are not working properly. The inspection of the system is recommended.

3.4.4 Availability

The Availability is the ratio shows the relation between APT and PBT. It shows the difference between the actual time and the planned. Besides the unit setup time and the unit delay time, an actual unit down time is considered here. It is a time when the work unit is not executing order production although it is available.

$$Availability = \frac{APT}{PBT}$$

The unit of Availability is measured in percent. It indicates how much a work unit is used for the production with respect to its available time. The higher the Availability, the better.

3.4.5 Effectiveness

Effectiveness is the ratio between the planned target cycle and the actual cycle. The planned target cycle is expressed as the planned runtime per item multiplied by the produced quantity. It is a planned time the work unit needed to produce a certain quantity of products. While APT is the time that work unit actually consumed for producing the same quantity of products.

$$Effectiveness = \frac{PRI * PQ}{APT}$$

The unit of Effectiveness is percent. The higher the Effectiveness, the better. High Effectiveness means the work unit processing procedure are stick to the plan. And the units work relatively well as expected. The effectiveness can be calculated in short periods, to show how effective a work unit will be during the production time. In the batch and continuous production, we prefer a variable that express the quantity of items can be produced in a specified period of time. It can be converted from PRI by specifying a fixed time period. And this method is useful in our approach to evaluate the performance of logistic variables in Chapter 3.5.

3.4.6 Quality Ratio

The QR shows the relationship between the good quantity and the produced quantity of the products.

$$QR = \frac{GQ}{PQ}$$

This variable is measured in unit percent. The higher the QR, the more the good products we have in a certain quantity of produced products. A low QR percent value may be caused to malfunction of the unit. As the QR decrease a maintenance might be needed.

3.4.7 Equipment effectiveness index

In this part we introduce two type of Equipment effectiveness indexes.

Overall Equipment effectiveness index (OEE index):

The OEE index is an integrated KPIs. It is a combination of Availability and Effectiveness of a work unit, and the quality ratio. The formula of OEE index is shown below.

$$OEE\ index = Availability * Effectiveness * Quality\ Ratio$$

After a simplification we get:

$$OEE\ index = \frac{PRI * GQ}{PBT}$$

As consequence we can get OEE index as the ratio between overall time for producing good items and the planned busy time. It indicates the efficiency of work units, work centers and the areas several work units. The unit of OEE index is percent. And the higher the OEE index, the higher the efficiency of work units. OEE index provides a better production information. Involving the production losses and the product quality. The calculation of OEE is only useful if the characteristic of the work unit processes would be comparable. Before starting a benchmark based on the OEE index the criteria for comparability should be checked.

Net Equipment effectiveness index (NEE index)

Another equipment effectiveness index is NEE index. It is a combination of the ratio between AUPT and PBT, the Effectiveness and the QR. The formula is shown below.

$$NEE\ index = \frac{AUPT}{PBT} * Effectiveness * Quality\ Ratio$$

After simplification we get:

$$NEE\ index = \frac{AUPT}{APT} * \frac{PRI * GQ}{PBT}$$

Compared with OEE index, NEE index modified the Availability element, substitute it as the ratio between AUPT and APT. Thus, it indicates the losses by work unit delays, cycle time losses and losses by rework. Its unit is also percent. And the higher the NEE index, the higher the efficiency.

3.5 Control system model

The control system model layer as the name says, the functions of variables in this layer is controlling the manufacturing system. Macroscopically speaking the control activity could be the production strategy, the overall management of the factory or the order scheduling. Microscopically speaking the control activity could be the specific control of a single work unit or the schedule of a single worker. By means of the software or the command from the manager. A good control system is able to increase the efficiency of the manufacturing system. As a result, reduces the cost and make it more profitable. Suitable or customized software play an important role in improving the efficiency of nowadays' automatic production lines. For a specific unit or specific plant their needs have a great difference between each other. In our discussion we will not go into details of this level. The variables we are interested in are those from logistic variables and order management variables.

Together with the status variables introduce in the previous chapter. The variables in this part will contribute a rough flow model of the materials as well as the products inside the production lines. Part of these variables are from ISO 22400-2. Again, speaking about the standard, all the variables should be considered. While in our approach we only discuss part of them in details. And build the connections between them and other variables belong to other model layers.

● Actual Order Execution Time (AOET)

This variable indicates the actual time from the start of the order until the time of the completion of the order. It is an actual time from measurement.

● Scrap Quantity (SQ)

During the production, part of the products may not meet the quality requirements. And they have to be scrapped or recycled. SQ indicates the quantity of them.

● Integrated Goods Quantity (IGQ)

For the KPI calculations GQ represents only a type of product, thus we need this variable IGQ that indicates the summed product count or quantity resulting from multiproduct production process.

Since IGQ is a variable consist of various products quantities. It is necessary to unify the measurement modes of different products, they need to be measured in the same unit of measure.

● Consumed Material (CM)

CM is the total quantity of raw materials consumed by the production process. CM is usually used in the denominator to calculate the related KPIs. Because of the different industrial processes, the state of the product may change. And for the specific process, the unify of the measurement unit is needed.

● Production Lost quantity (PL)

The production lost is the quantity lost during production. PL is inevitable and is strongly related to the process procedure. While a better choice of RM and good process design may reduce PL.

● Storage and Transportation Lose quantity (STL)

STL is the quantity lost during storage and transportation. During inventory calculation there might be inventory lost. And during movement from one place to another there might be material lost. A good management of material handling and inventory is needed to minimize this kind of lost.

● Other Los quantity (OL)

Besides the PL and STL, there might be unexpected quantity lost due to extraordinary incidents. Such as the natural disasters.

● Equipment Production Capacity (EPC)

EPC indicates the maximum production quantity of production equipment.

Control system model variables	
Variable name	**Acronyms**
Actual Order Execution Time	AOET
Scrap Quantity	SQ
Integrated Goods Quanty	IGQ
Consumed Material	CM
Production Lost quantity	PL
Storage and Transportation Lost quantity	STL
Other Lost quantity	OL
Equipment Production Capacity	EPC
Consumed Material per Item	CMI
Finished Goods Rate	FGR

Table 3.5.1 Control system model variables

With the variables above we are focusing on the performance's evaluation. By means of calculating the KPIs. In the table shows the KPIs that are more related to our other model layers.

Control system model performance indicators	
Indicator name	**Acronyms**
Throughput Rate	TR
Scrap Ratio	SR
Intergrated Goods Ratio	IGR
Loss Ratio	LR
Equioment Load Ratio	ELR
Raw Material Storage Ratio	RMSR
Finished Products Warehouse Ratio	FPWR

Table 3.5.2 Control system model performance indicators

3.5.1 Throughput Rate

TR is a process performance in terms of produced quantity of an order and the actual execution time of an order. This performance indicator is an important index for the efficiency in production.

$$TR = \frac{PQ}{AOET}$$

The unit of measure is Quantity unit / Time unit. It ranges from 0 to a value determined by the specific product. Typical time units to rate throughput are Hours or Days. This indicator is strongly related to the CFPW introduced in Chapter 3.1.4.

3.5.2 Scrap Ratio

SR is the ratio between scrap quantity and the produced quantity.

$$SR = \frac{SQ}{PQ}$$

It is ranged from 0% to 100%, and its unit of measure is percent. This ratio is influenced by the performance of work units. for different industrial process the ratio may varies much. The goal will be improving the facilities or the process to decrease SR. the lower the SR, the better. And the lower the cost due to scrap.

3.5.3 Integrated Goods Ratio

IGR is the relationship of the produced quantity of integrated goods to the consumed material.

$$IGR = \frac{IGQ}{CM} = 1 - LR$$

The unit of measure of IGR is percent. It is ranged from 0% to 100%. The higher the IGR, the better. Here using IGQ to evaluate the IGR instead of using PQ. The reason is that partial amounts of a specific quantity of finished goods might be defined as different finished goods according to their quality level. Using this integrated indicator, we consider the quantity of all products during production.

Since there might be various products, to calculate IGR, it is important to make sure that all products are measured in the same unit, or can be converted to the same unit.

IGR plus LR should equal to unity.

3.5.4 Loss Ratio

LR is the overall lost ratio of the manufacturing system. Generally, it involves production loss ratio, storage and transportation loss ratio and other loss ratio.

$$LR = PLR + STLR + OLR$$

Production Loss Ratio (PLR)

PLR is the relationship of quantity lost during production and the CM

$$PLR = \frac{PL}{CM}$$

Its range is from 0% to 100%. Unit of measure is percent. The lower the ratio, the better. PL is calculated as output minus input of the production.

Storage and Transportation Loss Ratio (STLR)

STLR is the relationship of quantity lost during storage and transportation to the CM.

$$STLR = \frac{STL}{CM}$$

Its range is from 0% to 100%. Unit of measure is percent. The lower the ratio, the better.

Other Loss Ratio (OLR)

OLR is the relationship of the quantity of loss not related to PL, STL to the CM.

$$OLR = \frac{OL}{CM}$$

Its range is from 0% to 100%. Unit of measure is percent. The lower the ratio, the better.

3.5.5 Equipment Load Ratio

ELR is the ratio between PQ and EPC. It represents the load level of the work units. EPC is either rated or maximum. The rated one defines the upper limit value of production equipment under a stable operation. The maximum one defines the upper limit value of production equipment demarcated before the delivery.

$$ELR = \frac{PQ}{EPC}$$

The unit of measure is percent. The minimal value is 0%, while the max value usually is 100%. It may exceed 100% if the system produced more products than the rated EPC.

The evaluation of ELR reflects the production state of equipment and production efficiency. With ELR the manager gets the information of performance and the utilization of equipment. ELR has a strong relationship with the production cost and profit.

In the case that ELR value is larger than 100%. The produced quantity may temporarily increase but in the mean time the performance of equipment might be impacted. Such as their reliability.

3.5.6 Raw Material Storage Ratio

The RMSR is the ratio between the Actual Raw Material Storage (ARMS) and the Capacity of RMS (CRMS).

$$RMSR = \frac{ARMS}{CRMS}$$

Its unit of measure is percent, and its range is from 0% to 100%. ARMS is a real-time value which represents the quantity stored in the RMS. CRMS is a fixed value after the plant is constructed. While it is still possible to be changed with renovation. In Chapter 3.3.1 we introduced a reference value for CRMS. Using the variables from this Chapter as elements, we can get it from the following formula:

$$RMCR = \frac{APT}{PBT * PRI} * CMI$$

$$CRMS = 8 * \frac{APT}{PBT * PRI} * CMI * 15$$

Consumed Material per Item (CMI) is related to the specific type of product. In our approach we assume that there are 8 hours per work day. With this formula we get a CRMS which is larger enough to store the amounts of raw materials for 15-workdays' usage. During the calculation we do not consider the PLR and STLR, the loss ratio will influence the ARMS element. And they are responsible to the differences between ARMS and CRMS, together with

3.5.7 Finished Products Warehouse Ratio

The FPWR is the ratio between Actual FPW (AFPW) and the Capacity of FPW (CFPW).

$$FPWR = \frac{AFPW}{CFPW}$$

Similar with the calculation procedure of RMSR. The unit of measure is percent, and its range is from 0% to 100%. 0% reflects a completely empty FPW, and 100% reflects a completely full FPW. CFPW is introduced in Chapter 3.3.2. In this part we introduce its detailed calculation. The calculation could be done following the formula:

$$FGR = \frac{APT}{PBT * PRI}$$

$$CFPW = 8 * \frac{APT}{PBT * PRI} * 15$$

Finished Goods Rate (FGR) is the quantity of finished goods produced per hour. The time unit of APT, PBT and PRI is hour. First, we calculated how many items can be produced per hour. Then according to the criteria introduced in Chapter 3.3.2. We have the CFPW value.

3.6 Financial system model

This model layer includes the variables related to finance. Simply speaking, in this part we are considering the cost and the profitability of the manufacturing system. At first, we introduce three basic variables: Operating Revenue (OR), Total Revenue (TR) and Total Cost (TC). Their relationship is described by the following formula:

$$OR = TR - TC$$

This is a general description of the Income. While we consider the financial system in industrial aera. A much more complex system consists of numbers of variables is needed. During our development of this model layer, a book named 'L'impresa. Teoria, organizzazione, strategia, tecniche economiche e contabili' helped us a lot. The majority part of the variables we discuss are introduced by this book. And we modified some of them to fit our model. Basically, in this model layer, we build the relationship among the financial variables. They act as the elements for calculating the financial KPIs.

First, we have a short description of the variables we need.

Net Capital (NC)

Assets (AS) and Liabilities (LI)

$$NC = AS - LI$$

Other variables will be introduced in the corresponding performance evaluation part below. In the table listed the KPIs we will discuss in this part.

Financial system model performance indicators	
Indicator name	**Acronyms**
Investment in Working Capital	IWC
Investment in Fixed Assets	IFA
Sales Prices index	SPi
Total Real Cost of Labor	TRCL
Real Cost of the Capital	RCC
Gross Return Rate on Capital	GRRC
Return On Investment	ROI
Net Operating Return	NOR
Return on Equity	ROE
Energy Consumption Ratio per Finished Good	ECRFG

Table 3.6.1 Financial system model performance indicators

3.6.1 Investment in Working Capital

Investment in Working Capital refers to the investment that the investor uses to obtain current assets, that is, the funds that are paid in advance before the project is put into production and used for turnover in the production and operation process after the project is put into production. Here we mainly consider its relations to Total Warehouse, Commercial Credits and Commercial Debts. Their relationship is shown below.

$$ICO = TI + CC - CD$$

Total Inventory (TI)

TW refers to the investment in the inventory of all the materials, semi-products and finished goods.

Commercial Credits (CC)

CC is a credit granted by one business to another during the sale of goods. For example, the raw material manufacturer grants the credit to the product manufacturer, or the product manufacturer grants the product wholesaler, and the product wholesaler grants the credit to the retail enterprise. The main forms of commercial credit are: purchase of goods on credit, advance payment and commercial draft.

The investment in the raw materials and the energy consumed are included in CC.

Commercial Debts (CD)

Commercial liabilities are monetary liabilities assumed by trusted banks paid out of assets or capital. Business liabilities are debts owed by a business to creditors. It is expressed in money and needs to be repaid in assets or services. Debt is an important source of funding for business enterprises.

3.6.2 Investment in Fixed Assets

Investment in fixed assets is expressed in the form of currency, the workload of construction and purchase of fixed assets by enterprises within a certain period of time, and the changes in related expenses. Including real estate, buildings, machines, machinery, means of transportation, and enterprises for capital construction, renovation, major repairs and other fixed asset investments, etc.

In our approach we consider IFA is the sum of GIIA, GTI and FAI minus NETC.

$$IFA = GIIA + GTI - NETC + FFA$$

Gross Investments in Intangible Assets (GIIA)

Intangible assets refer to identifiable non-monetary assets without physical form. Intangible assets can be divided into broad sense and narrow sense. Intangible assets in the broad sense include financial assets, long-term equity investment, patent rights, trademark rights, etc. They do not have physical entities, but represent certain legal rights or technologies. However, in accounting, intangible assets are usually understood in a narrow sense, that is, patent rights, trademark rights, etc. are called intangible assets. Investment in intangible assets means that investors invest in patent rights, non-patent technologies, trademark rights, land use rights, etc. The value of intangible assets should be determined according to the amount agreed by both parties, and necessary documents should be used as the basis for processing.

GIIA is the total amount of investments in intangible assets.

Gross Technical Investments (GTI)

Technical investment refers to the investment made by adopting new technology, new process and new equipment to promote technological development. Including all kinds of investment required for the design of new technology software, investment in testing and trial production of new technology equipment and related scientific research, and investment in the introduction of new technology software and new technology equipment

Net Eliminations of Technical Capital (NETC)

Technical capital refers to a group of renewable capabilities in the field of production, technology and support, and its notable form is intellectual property rights such as patents and know-how. The technical capital owned by the investors is considered as a negative value in the IFA. Which is an elimination of the technical investment.

Fixed or long-term Financial Assets (FFA)

Fixed assets refer to non-monetary assets that are held by an enterprise for the purpose of producing products, providing labor services, leasing or operating management, and have been used for more than 12 months, and whose value reaches a certain standard, including houses, buildings, machines, machinery, transportation, etc. Tools and other equipment, utensils, tools, etc. related to production and business activities. Fixed assets are the labor means of enterprises and the main assets that enterprises rely on for production and operation.

3.6.3 Sales Prices index

The product sales price index, also known as the "commodity sales price index", is a quality index and a general index that reflects the comprehensive changes in the prices of various commodities.

$$SPi = \frac{GPV}{RPV}$$

Gross Production Value (GPV)

Gross production value, a statistical term, period indicators (month, season, year), refers to the sum of the value of goods and services produced by the resident units of the material production department within a certain period of time, reflecting the value of the production and operation activities of the material production department.

Real Production Value (RPV)

RPV is the sales price of the product multiply the quantity that can be produced without losses. Considering the losses, RPV should be larger than GPV.

3.6.4 Real Cost of Labor

Labor service cost refers to the cost incurred by the enterprise for providing labor services. Compared with the company's labor service income, it can be within the company or outside the company. Such as providing repair and moving services, the corresponding labor wages, benefits, labor insurance, and related expenses are labor costs.

$$TRCL = \frac{TNCL}{IPACL}$$

Total Real Cost of Labor (TRCL)

TRCL is the real cost spent in a certain period, for example, one year or one month.

Total Nominal Cost of Labor (TNCL)

TNCL is a nominal value among a very long time period. It is a fixed value probably set by government policy.

Implicit Prices index in the Average Cost of Labor (IPACL)

IPACL is the ratio between average cost at cost of the basic year.

3.6.5 Real Cost of Capital

The cost of capital is the opportunity cost of investing capital. This cost is not the actual cost paid, but a lost income, which is the income of other investment opportunities abandoned by using capital for this project investment, so it is called opportunity cost. For example, the purpose of an investor investing in a company is to obtain returns. Whether he is willing to invest in a specific company depends on whether the company can provide more returns. To do this, he needs to compare the company's expected rate of return with the expected rate of return of other such venture capital opportunities. If the company's expected rate of return is higher than all other investment opportunities, he will invest in the company. The benefit of other investment opportunities he forgoes is the cost of investing in the company. Therefore, the cost of capital is also called the trade-off rate of the investment project and the minimum acceptable rate of return.

$$RCC = (EATC + NPRIC) * GTC$$

Economic rate for the Amortization of the Technical Capital (EATC)

Normal Profit rate of Return on Invested Capital (NPRIC)

Gross Technical Capital expressed in real terms (GTC)

3.6.6 Return on Capital

The rate of Return on Capital refers to the ratio of invested or used funds to related returns (returns are usually expressed as interest and/or profit sharing). It is used to measure the effect of the use of invested funds. RRC is a metric used to evaluate the historical performance of a company or its business unit. At the same time, the return on capital can also be used to measure the total capital return of the macro economy. The ratio of the output of capital input to the capital stock is the total return on capital. Where the rate of return on capital is high, capital will flow in in the next period, which in turn will increase investment and accelerate economic growth.

$$GRRC = \frac{OR}{TOC} = \frac{ROS}{RTTC}$$

Gross Return Rate on Capital (GRRC)

Operating Revenue (OR)

OR refers to the income obtained from the main business or other businesses. Refers to the monetary income obtained by commercial enterprises from selling goods or providing labor services within a certain period of time.

Tangible Operational Capital (TOC)

Tangible assets are the main type of assets that companies use to produce their product and service.

Return on Sales (ROS)

Return on sales is an efficiency indicator for measuring a company's profit from sales, and is calculated on the basis of net profit after tax and total sales. Return on sales helps companies determine how effectively they are monetizing sales. Again, this is an indicator of management effectiveness.

$$ROS = \frac{OI}{GPV}$$

Recovery Time of Tangible Capital (RTTC)

$$RTTC = \frac{TOC}{GPV}$$

3.6.7 Net Profit of Operational Capital

Net Operational Capital is the balance of the total current assets of the enterprise minus various current liabilities. Reflects the amount of current assets financed by long-term liabilities. In this part we will discuss the profit that the OC could provide.

Return On Investment (ROI)

Return on investment (ROI) refers to the value that should be returned through investment, that is, the economic return that a company gets from an investment activity. It covers the profitability goals of the business. Profit is related to the property necessary to put it into business, since the manager must make a profit from investments and existing property.

It refers to the economic return that an enterprise obtains from an investment in an investment commercial activity. It is a ratio used to measure the profitability of an enterprise, and it is also a comprehensive indicator to measure the operating effect and efficiency of an enterprise.

In this part we consider ROI as the ratio between Net Operating Margin (NOM) and Net Operational Capital (NOC).

$$ROI = \frac{NOM}{NOC}$$

It can be seen from the formula that enterprises can increase the return on investment by "reducing sales costs, increasing profit margins, and improving asset utilization efficiency".

Net Operating Return (NOR)

The theory of net operating income believes that no matter how the financial leverage changes, the weighted average cost of capital of the company is fixed, and the total value of the company remains unchanged. Therefore, the company cannot use financial leverage to change the cost of weighted average capital, nor can it improve by changing the capital structure. The value of the company, which determines the value of the company should be operating income

$$NOR = GRRC - EATC * POT$$

Percentage share of Operative Capital in Technical capital (POT)

POT indicates the share ratio of operative capital in the technical capital. EATC*POT is the Economic rate for the Amortization of the Operative Capital.

3.6.8 Return on Equity

ROE is the percentage of net profit and average shareholders' equity, and is the percentage ratio obtained by dividing the company's after-tax profit by net capital. This indicator reflects the level of return on shareholders' equity and is used to measure the efficiency of the company's use of its own capital. The higher the indicator value, the higher the return on investment. This indicator reflects the ability of self-owned capital to obtain net income.

$$ROE = \frac{OI}{NC}$$

3.6.9 Comprehensive Energy Consumption

CEC is the ratio between all the energy consumed in a production cycle and the produced quantity. This is a KPI introduced in ISO 22400-2, here we modified it to calculate the energy cost for producing a product unit.

Energy Consumption Ratio per Finished Good (ECRFG)

We have two variables, one is Planned Energy Consumption per Finished Good (PECFG), another is Actual Energy Consumption per Finished Good (AECFG). The EFCG Rate is in relation to them and the formulas are introduced below:

$$ECRFG = \frac{AECFG}{PECFG}$$

$$PECFG = \left(\sum ECRi * ECi\right) * PRI$$

$$AECFG = \left(\sum ECRi * ECi\right) * ARI$$

● Energy Consumption Rate of certain kind of energy (ECR)

● Energy Cost of certain kind of energy (EC)

● Actual Run Time per Item (ARI)

The unit of measure for ECFG is Euro/Item. the minimal value is 0 and the maximum value is dependent on the specific product.

The unit of measure for ECRFG is percent. The minimal value of this KPI is 0%, the maximum value is dependent on the actual producing process. It can exceed 100%. The lower the KPI, the less the energy cost per item.

3.7 Social model

The function of social model layer is to make a description of the social influences caused by the manufacturing system. Provide the plant owner information about the impact of this company on the surrounding, both good and bad. Or provide a reference suggestion to the manager who are planning to design a new plant.

In this model we focus mainly on two types of influence. One is the company's impact on the surrounding environment, another is the impact on the surrounding economy. Variables ae not a good choice to evaluate the social model. We designed the questionnaires for gathering information from nearby residents as well as the factory employees.

3.7.1 Environmental impact

Considering the influences to the environment, the pollution is a key factor. The pollution can come in various forms. Such as air pollution, water pollution and industrial waste. Generally, a factory can rarely improve the environmental pollution, but we still set a selection for it.

Besides of the pollution, the factory may have impact also on the traffic systems nearby. The road may be renovated or damaged. And the traffic may be improved with more buses and taxis. Or on the contrary more vehicles lead to traffic jam.

3.7.2 Economical impact

A new factory can provide more job opportunities, while it will also be a new competitor or collaborator of the nearby factories. The impact will be two-way, indirect or direct. A factory may also create economic benefits for the local area depends on its operations. We will provide a questionnaire in next part and discuss the impacts in detail.

3.7.3 Questionnaire

Questionnaire for plant impact on your daily life

This questionnaire is designed to collect your advices, please choose the most suitable one according to your knowledge and experience.

Thanks for your patience and collaboration.

Please mark the blank with the following instructions:

Choose the level of impact that this plant brings to your life.

First part: bad environmental impacts

Dose the plant	Definitely not	No	I don't know	Yes	Definitely yes
Make the air worse					
Make the water worse					
Leave waste nearby					
Generate noise					
Second part: good environmental impacts and economical impacts					
Improve the road quality nearby					
Have a good impact on traffic					
Provide more job opportunities					
Provide you with the opportunity to earn money					
Have a good impact on local economy					

If you have any other advice, please write here:

Table 3.7.1 Questionnaire for plant impact on your daily life

All the questions are ranked in five levels. For the first part, the corresponding value of each choice are 2, 1, 0, -1, -2 from 'Definitely not' to 'Definitely yes'. In the second part the values are -2, -1, 0, 1, 2 with respect to the choice from 'Definitely not' to 'Definitely yes'. An average value is calculated for each question. A positive value indicates that the plant has a good impact, the higher the value, the better. Value 0 indicates no impact. And a negative value leads to a result of very bad impact.

4. Overview of the models and the connections between model layers

After the development of the Production Hierarchical Models, in this chapter we will make a summarize of them. This modeling process can be used in two ways.

First the modeling can be applied to the manufacturing system which is on planning stage. It is possible to construct a digital factory for the simulation. The variables will be the inputs and the outputs are the KPIs for different layers. With the help of simulations, the designer may predict the performance of this manufacturing system as well as the profitability. It will be a good tool to help the designer to make decisions. Avoiding the cost increment due to unexpected issues.

4.1 Overview of the models

Production Hierarchical Models		
Model layer name	**Inputs variales**	**Outputs variables and KPIs**
Layout model	TA OSA TRW ATRW RTRW DRW ST ATWF RTWF DWT AMA RMA TPP ASA RSA APP	FUR SEF TRW TWF MA SA
3D model	HP	
PLant service model	RMCR RMUR FPLR FPMR	FRMS FFPW
Status variables model	APWT APAT AUBT PRI APT PBT PQ GQ AUPT	WE AE UE Availability Effectiveness QR OEEi NEEi
Control system model	AOET SQ IGQ CM PL STL OL EPC CMI FGR CMI	TR SR IGR LR ELR RMSR FRWR
Financial system model	OR TR TC NC AS LI TI CC CD GIIA GTI NETC FFA GPV RPV TRCL TNCL IPACL EATC NPRIC GTC GRRC OR TOC ROS RTTC NOM NOC POT AECFG PECFG ECR EC ARI	IWC IFA Spi TRCL RCC GRRC ROI NOR ROE ECRFG
Social model		

Table 4.1.1 Production Hierarchical Models

4.2 The connections between model layers

As we can see in the table 4.1.1, each layer includes the variables related to its model's type. There are time variables, spatial variables, logistic variables and quality variables. While all the layers are divided from the same manufacturing system. They are all closely related. Part of the variables or KPIs of a specific model layer will be used as elements for calculation in other layers.

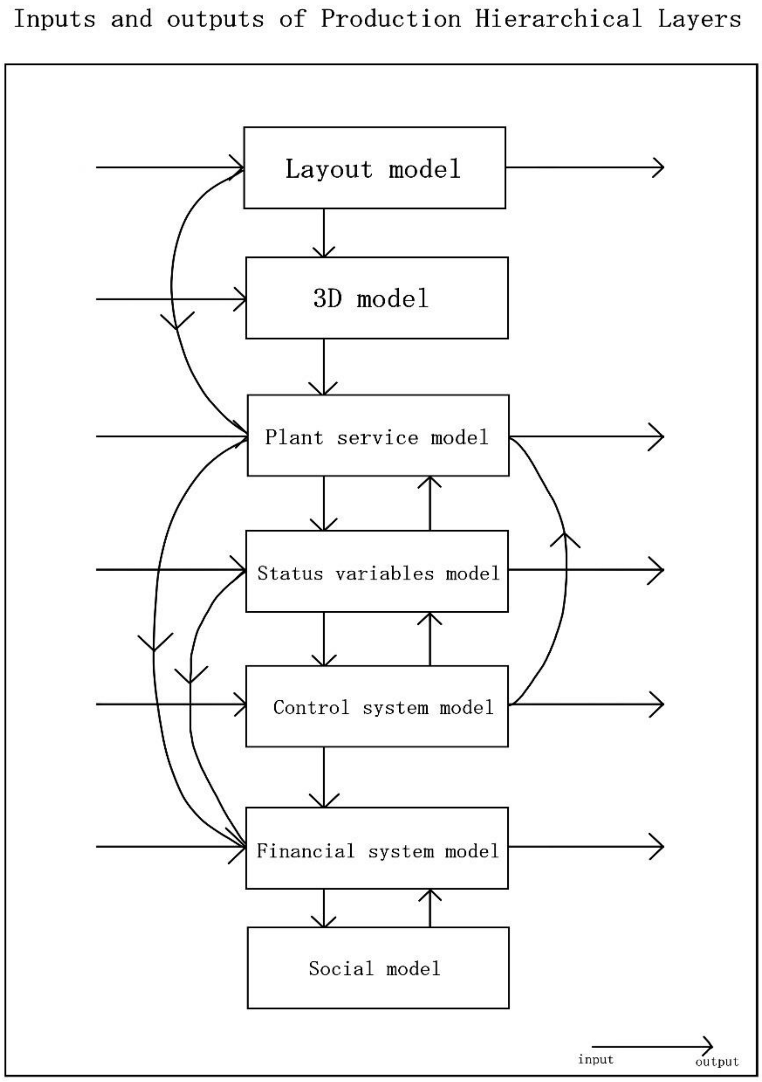

Figure 4.1 Inputs and outputs of Production Hierarchical Layers

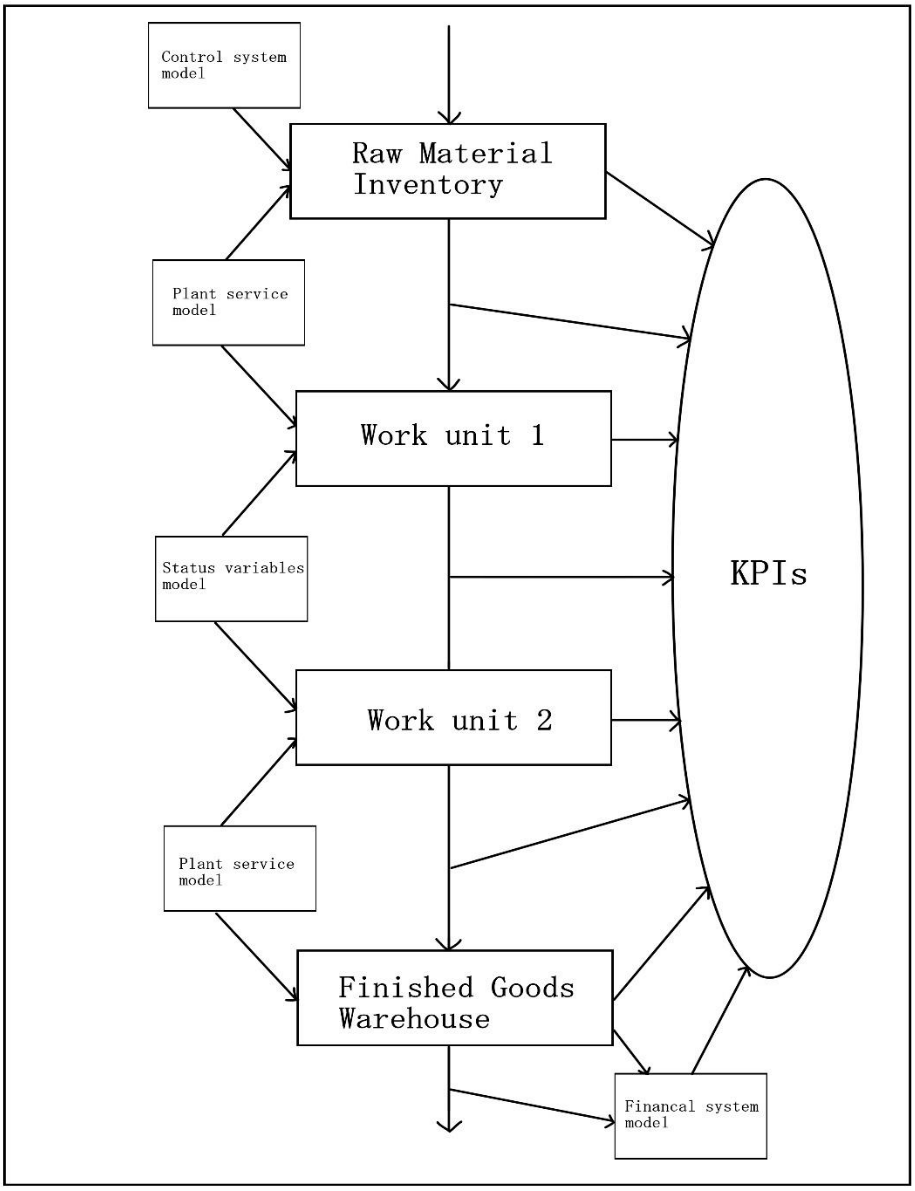

Figure 4.2 Example of Queue model

For a practical production line, after the modeling procedure. It is able to input the variables in different layer level and get its corresponding KPIs. Thus, makes it possible to evaluate the different type of performances dividedly. Such as the logistic performance, the efficiency and the stability of material handling system.

5. Application to a Practical case

The theoretical model we developed need to be verified by applying it to the practical cases. Collecting more practical data the model can be further modified.

In this chapter we are going to develop a hierarchical model for a production line which was in planning stage. Our goal is trying to show an example that how this hierarchical model works. This production line consists of two different CNC machines, a type of robot for transporting items, a mechanical arm robot, one motorized linear slide type Festo DGL, length of approx. 3 meters and one Festo warehouse unit complete with trolley with No. of 3 x 700 mm automated conveyor belts.

As it is not a manufacturing system actually put into production. Part of the variables will be missing. In this paper we will pay more attention on the available variables. And the target is to build a model which set the product's variables as inputs. Once deciding the product to manufacture, the model could output the financial variables such as the Cost per Item. The procedure of analyzing the performances for each model layer will be introduced in this chapter.

Let's beginning with the introduction of the important facilities of this production line.

Figure 5.1 Photo of the production line

Concept MILL 105

Concept MILL105 is an CNC milling machine.

Figure 5.2 Concept MILL 105

Work area	
Travel in X longitudinal	200 mm (7.9")
Travel in Y latitudinal	150 mm (5.91")
Travel in Z vertical	250 mm (9.84")
Min. distance spindle nose - table	95 mm (3.74")
Max. distance spindle nose - table	245 mm (9.65")
Table	
Clamping area (L x W)	420 x 125 mm (16.54x4.92")
T-slots: quantity, width, spacing	2 x 11 x 90 mm (2x0.43x3.54")
Max. table load	10 kg (22 lb)
Milling spindle	
Speed range	150 - 5000 rpm
Motor power 3 phase asynchronous motor	1.1 kW (1.48 hp)
Max. torque	4.2 Nm
Axis data	
Rapid motion speed X / Y / Z	5 m/min (196.85 ipm
Max. feed rate X / Y / Z	0 – 5 m/min (0 – 196.85 ipm)
Feed power X / Y	2000 N
Feed power Z	2400 N
Accuracy	
Step resolution (X / Y / Z)	0.0015 – 0.001 mm
3 phase step motors	(0.00006 – 0.0004")
Average positioning variation in X / Y (VDI/DGQ 3441	5 µm (0.0002")
Average positioning variation in Z (VDI/DGQ 3441)	5 µm (0.0002")

Tool change	
No. of tool stations	10
Tool selection	Directional logic
Max. tool diameter	55 mm (2.17")
Max. tool length	50 mm (1.97")
Max. tool weight	0.7 kg (1.54 lb)
Tool changing time T1 / T2 / T3	9/7.5/7.5 s
Power consumptions	
Power supply	1.4 kW (1.88 hp)
Dimensions	
Dimensions W x D x H	1135 x 1100 x 1100 mm (44.69 x 43.31 x 43.31)
Total weight	400 kg
Compressed air	6 bar
EMCO WinNC Controls	
Sinumerik Operate 840D sl / 828D	
Fanuc Series 31i	
Heidenhain TNC 640	
Heidenhain TNC 426/430	
Fagor 8055	
CAM Concept	

Figure 5.3 Technical data of Concept MILL 105

Concept TURN 105

Concept TURN 105 is an CNC turning machine.

Figure 5.4 Concept TURN 105

Work area	
Swing over bed	180 mm (7.09")
Swing over cross slide	75 mm (2.95")
Distance between spindle noses	236 mm (9.29")
Max. turning diameter	75 mm (2.95")
Max. part length	121 mm (4.76")
Max. bar-stock diameter	20 mm (0.79")
Height of centers	90 mm (4.76")
Travel	
Travel in X	55 mm (2.17")
Travel in Z	172 mm (3,54")
Main spindle	
Speed range	150 – 4000 rpm
Max. torque	14 Nm
Spindle diameter at front bearing	45 mm (1.77")
Spindle bore	20.5 mm (0.81")
Main motor	
Drive power	1.9 kW / 2.6hp
Tool turret	
No. of tool stations	8
Tool-cross section	12 x 12 mm (0.5 x 0.5")
Shank diameter for boring bars	16 mm (0.63")
Turret indexing time (T1/T2/T3=45°/180°/315°)	1.4 / 3.5 / 5.5 s

Feed drives	
Rapid motion speed X/Z	5 m/min (196.85 ipm)
Feed force X/Z	2000 N
Work feed X/Z	0 – 5 m/min
Positioning variation Ps (acc. VDI 3441) in X/Z	5 µm (0.0002")
Tailstock	
Quill stroke	120 mm (4.72")
Quill diameter	35 mm (1.38")
Coolant system (option)	
Tank capacity	35 l
flow volume	15 l/min
Pump power	0.5 bar
Dimensions	
Height of center above floor	267 mm (10.51")
Dimensions W x D x H	1135 x 1100 x 1030 mm (40.55 x 44.69 x 43.31")
Total weight	350 kg
EMCO WinNC control types	
Sinumerik Operate 840D sl/828D	
FAGOR 8055 TC	
FANUC Series 31i	
CAMConcept	

Figure 5.5 Technical data of Concept TURN 105

Robot mobile Robotino Premium

Robotino Premium is a mobile robot system used for the delivery of materials or the finished goods.

Figure 5.6 Robotino Premium

Technical data:

Diameter: 450 mm, height incl. controller housing: 290mm

Total weight: approx. 20kg (without mounting tower), payload: max. 30kg.

Permit speeds: 10 km/h

Power supply: 12V

Forklift load veering capacity: up to 4kg

Total Cost in euro: 8600 +22% tax.

Robot Industriale Mitsubishi RV-2SDB

Mitsubishi RV-2SDB is an industrial robot designed to answer the needs of users who want to create compact and highly flexible production facilities to cope with shortened product life cycles as well as the diffusion of small and high-density product groups in recent years, such as personal computer related devices, information terminal devices and small car-mounted electronic devices.

Figure 5.7 Mitsubishi RV-2SDB

Technical data:

Speed of motion: 4.4 mm/sec

Load: Maximum load 3 kg, Rating load 2kg.

Rated input voltage: 24VDC

Rated input current: Approx. 7mA

5.1 2D Layout

2D layout layer performance evaluation	
The dimensions and the positions of facilities	
↓	
2D layout of the manufacturing system	
↓	
Floor occupation, Material handling route	Logistic variables from Control system layer
↓	
Floor spatial utilization, Stability of the Material handling devices	

Table 5.1.1 2D layout layer performance evaluation procedure

The parameters for a 2D layout can be measured or directly collected from the design diagram. In our case the dimensions are the technical data of each facility. With the help of SolidWorks, we drew this layout. To calculate the KPIs in this layer, also the logistic variables from Control system layer are needed. The final outputs are the KPIs of floor spatial utilization and of Stability of the Material handling devices.

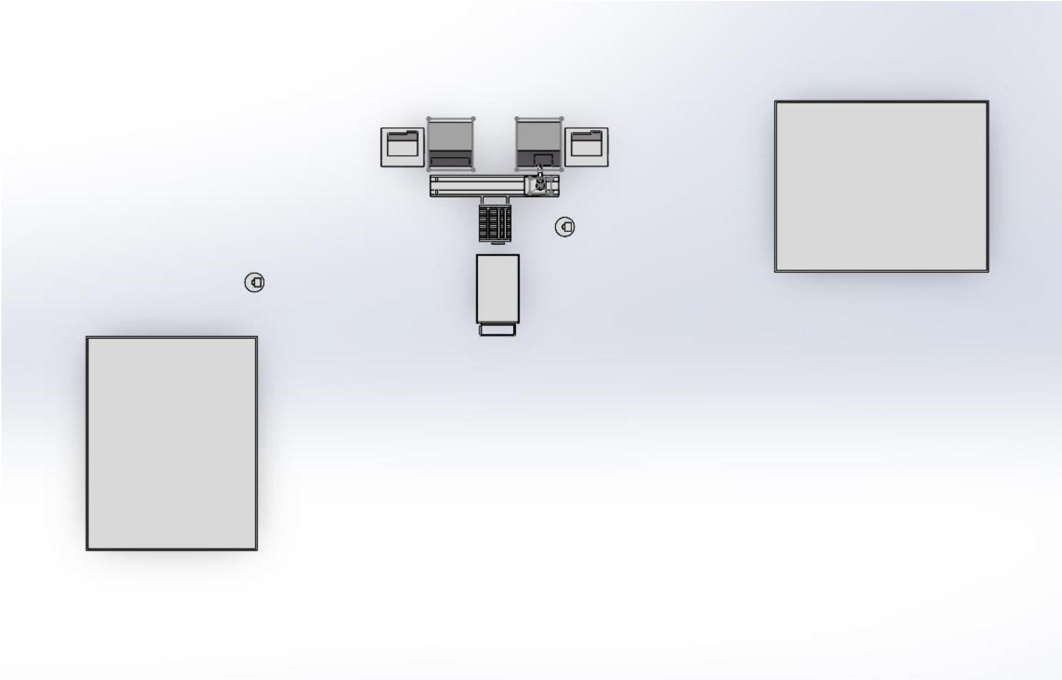

Figure 5.8 2D Layout of the production system

5.2 3D Model

In this layer only one variable Height is provided. We have a vertical dimension of all the facilities. The 3D modeling was accomplished in SolidWorks.

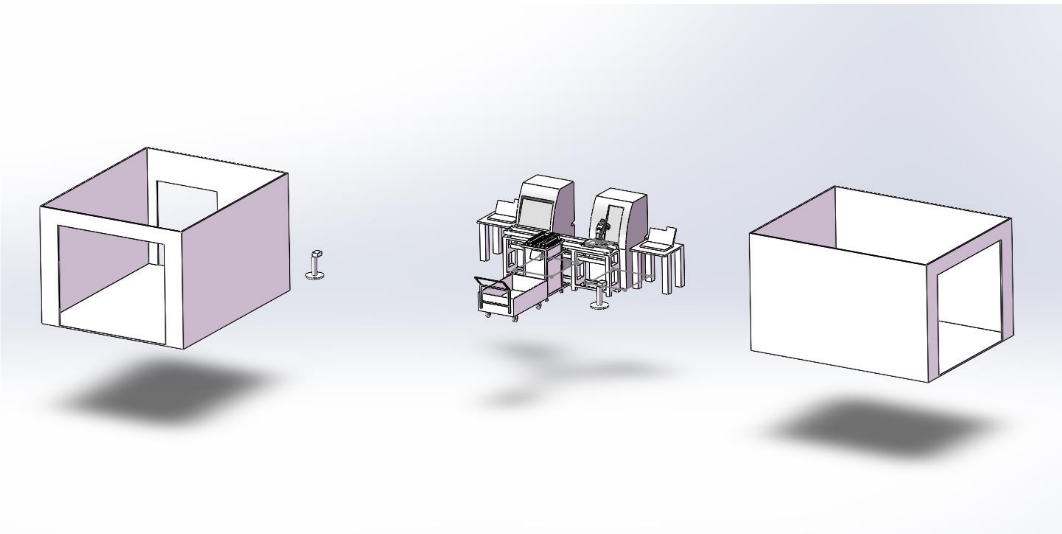

Figure 5.9 3D Layout of the production system

5.3 Plant service

Plant service layer performance evaluation	
Find/record Service facilities required/exist	
↓	
The inventory of raw materials and finished goods	
↓	
Time variables from Status variables layer	Logistic variables from Control system layer
↓	
The strategy for transportation of raw material and finished goods	

Table 5.1.2 Plant service layer performance evaluation procedure

5.4 Status variables

Status variables layer performance evaluation	
Define the type of workers and work units	
↓	
Technical parameters for specific unit	
↓	
Time variables and Quality variables	Logistic variables from Control system layer
↓	
Efficency of worker and work unit, product quality ratio and equipment effectiveness index	

Table 5.1.3 Status variables layer performance evaluation procedure

5.5 Control system

Control system layer performance evaluation	
Order managements of the manufacturing system	
↓	
Time variables from Status variables layer	Logistic variables, quality variables
↓	
The analysis of the throughput, scrap and loss of production line, the capability of inventory facilities	

Table 5.1.4 Control system layer performance evaluation procedure

5.6 Financial system

Financial system layer performance evaluation
Classification of the assets, liabilities and investments
↓
Financial variables
↓
Building relationship between financial variables
↓
The cost, investment and profitability analysis, return on equity and energy consumption

Table 5.1.5 Financial system layer performance evaluation procedure

5.7 Social impact

In this layer no variable is involved. Using the questionnaire to gather advices.

6. Conclusions and Further research

In our approach we were focusing on the evaluation of various type of variables in different layer level. This hierarchical model describes the manufacturing system from different aspects. The KPIs system may help the analyzing of performance. While it is still a framework model, not everything is considered in detail. As we discussed in the chapter 3 during the development of this model, there are many good points exist which could be studied furthermore.

In this paper we only developed the models and briefly introduced the analysing procedures with a production line in planning stage. Lacking of the practical processing data and the actual variables, the outputs can not be calculated as the real values. In the model some performance evaluations are related to the reference variables, they are coming from either textbook or empirical data. The practicality of this model will be improved if more practical values are used to modifying the evaluation system.

For further research on this model, the applying to a real manufacturing system is recommended. With a running factory, the actual time variables, the actual logistic variables and the actual quality variables can be measured by means of sensors or other measurement devices. Thus, all the KPIs can be calculated in real value.

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