POLITECNICO DI TORINO

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Master's Degree Program in Automotive Engineering

Master's Degree Thesis

Production system hierarchical model

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Abstract

In the era of Industry 4.0, for the manufacturing, everything is connected thanks to the continuous development of automatic control and advanced sensor technology, and we put forward a concept of ‘Digital Factory’ which uses digital technology for modeling, communications and to operate the manufacturing process. By this way, we can fully monitor, control and optimize all the production variables in the manufacturing system in real-time.

In this article, we introduce a practical industrial case, which is the production of corncob powder for fuel. The whole production system transfers the raw materials corncobs into powder. Then we will develop a hierarchical production system model and apply this model to one of the devices in our practical production system case.

Key words: Industry 4.0, production system, hierarchical model, corncobs powder, digital factory

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Chapter 1: Background

The concept of the Industry 4.0 is proposed by German in 2011 Hanover Industrial Expo, it is just like other 'Hot word' recent years, AI, block chain, autonomous driving e.g., which are based on the information technology, changing our life gradually. Thanks to the introduction of computer and Internet, our life becomes easier and now we rely on the technology much more than ever.

The same process is happening in manufacturing area. Now we have already achieved fully automatic manufacturing and digital management of manufacturing in many companies. The new trend is that the new technology allows continuous interactions not only among humans and between human and machines, but also among machines. This gives us a better manufacturing environment. So, we can consider this trend is a new industrial revolution.

1.1 The history of industrial revolution

1.1.1 The 1st industrial revolution

It refers to the technical revolution happened in 60s of 19th century in Britain, which is the first revolution in the history of human technology, it is not only a technical revolution, but also a deep society evolution.

The mark of this revolution is the wide using of steam engine, the factories replace the manual fields. Regarding the social relations, the peasant class disappears, while the industrial bourgeoisie and proletariat rises.

Britain, who finishes the revolution first, became the most powerful country in the world at that time.

For manufacturing, people began using power of steam instead of their muscle, so more and more manufacturing machines based on steam engine make the processing more efficient and powerful.

1.1.2 The 2nd industrial revolution

It happened in the 60s of 19th century among European, the US and Japan, the mark of this industrial revolution is the usage of electricity, which allow the human society to evolve to 'electric era'.

During this period, the human invented electric generator, internal combustion engine and telecommunication. These inventions stimulated the rapid productivity improvement. The capitalistic production was booming, sharpening contradictions among social classes and raise the unbalances among countries, which foreshadowed the following two world wars.

The electric motor, which is much better than steam engine as the power of manufacturing machines, changes the manufacturing process, people have ability to process metal easily then to build many kinds of machines that can serve human in many areas. Besides, the invention of production-line makes the mass production possible.

1.1.3 The 3rd industrial revolution

From 50s of last century, the world witnessed the appearances and developments of the technology of atomic energy, aerospace and computer, then artificial synthetic material, molecular biology and genetic engineering. These technologies mark the 3rd industrial revolution in human history.

This revolution deeply changed the way of thinking and lifestyle of humans, as well as the way of manufacturing. The use of CNC machines let people process components more precise and efficient. And industrial robotics have raised the production rate to a new stage.

1.1.4 The 4th industrial revolution

Nowadays, the new coming era of AI, VR, clean energy etc., represent the approaching of the 4th industrial revolution. This revolution, so called ‘Industry 4.0’ which proposed by German, born under the circumstance that human is facing the crisis of resource and the environment of the earth is becoming worse, so the main topic of this revolution is ‘Green’, which means we use the most eco-friendly way of manufacturing without sacrificing the nature. Thanks to the advanced IT technology today, we can totally monitor and control each single step of the whole manufacturing process, and by interconnecting, each device can communicate so to improve the efficiency.

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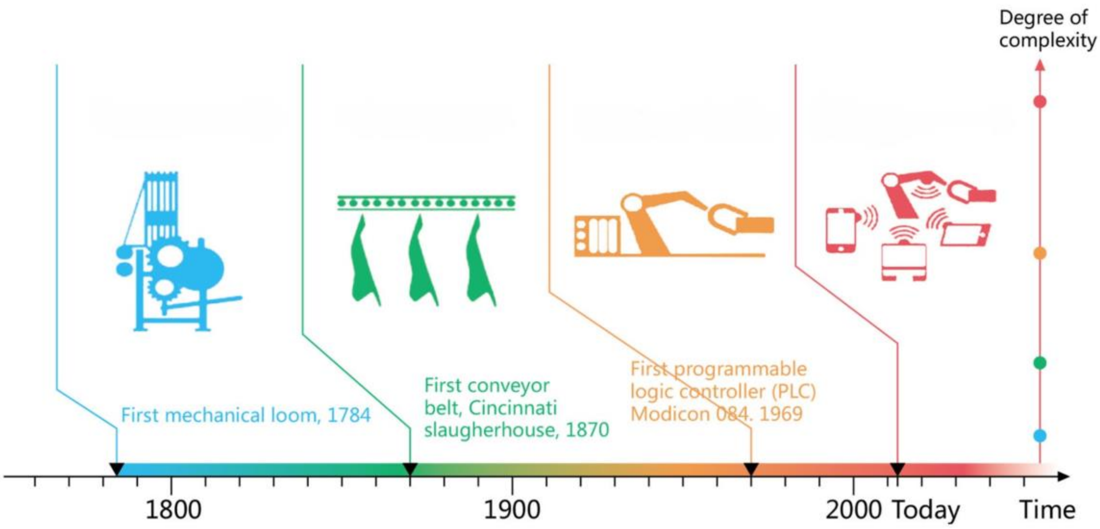

Figure 1 The revolution of industry

1.2 Manufacturing in Industry 4.0 era

In a brief word, the Industry 4.0 refers to the combination of Information Communication Technology (ICT) and Cyber Physics System (CPS). For manufacturing, we pay more attention on CPS, which is that through powerful background computing and simulation each object and event in the real world is converted into digital information and stored, analyzed and controlled. For example, Amazon's trading platform is a simple CPS model, and the platform will be an event, every item, every customer, every business, etc. is transformed into data storage and analysis, which achieves the functions of targeted advertising, merchant quality screening, etc. If we apply this technology to industrial manufacturing, the administrator can know all the events happening in the production line in real time and check the status of each device. The equipment can even adjust its own parameters according to its own production status, so the profit of the manufacturing industry will be enlarged a lot. Finally, all plant equipment data is integrated on the CPS system. The CPS can predict the time of work required for each machine, ensure the output of the major plants under the CPS system by arranging appropriate work tasks for the equipment, to achieve best quality and speed of the product.

Figure 2 Everything is connected in 5G

But there is still a long way to go, nowadays though some large corporations realize intelligent production in part of their production, it is far away from totally interconnection, let alone small to medium enterprises. The current technology is not enough to support the idea, but with the coming of 5G ICT, the data can be transferred will be much higher than ever, it ensure the transformation requirements of Industry 4.0, like visual AI detection system, who need a very little delay (<10ms).

Chapter 2: A production system

The production system is a part of the manufacturing companies that produce the products, which has comprehensive functions of sales, design, processing, delivery, etc. The production system is an orderly conversion of the inputs of various production factors into the products. Where input, conversion process, and output are the basic components of a production system. Among them, input Refers to processing objects and other factors of production, such as raw materials, materials, personnel, energy, etc.; conversion process is the production process refers to physical, positional conversion, such as manufacturing, transportation, etc.; output represents the result of subsequent formation and output, such as tangible products or intangible services.

In our case, we focus on a production system of a small factory, which produce the powder of corn cobs.

2.1 The product and production process

2.1.1 Corncobs powder

The corncobs are the by-products of corns, after removing the edible parts from corns. In the past, it is used as the fuel or just be incinerated, so the utilization is very limited. Nowadays, people have found many advantages of this ‘agriculture waste’.

It has the advantages of uniform structure, suitable hardness, good toughness, strong water absorption and good wear resistance. If we process it into powder, it can be used in many areas.

Corncobs powder use in the following applications:

- Industrial source of the chemical furfural.
- Fiber in fodder for ruminant livestock (despite low nutritional value)
- Water in which corncobs have been boiled contains thickeners and can be added to soup stock or made into traditional sweetened corncob jelly
- Bedding for animals – cobs absorb moisture and provide a compliant surface

- Ground up and washed (then re-dried) to make cat litter
- A mild abrasive for cleaning building surfaces, when coarsely ground
- Raw material for bowls of corncob pipes
- As a biofuel
- Charcoal production
- Environmentally friendly rodenticide
- Soil conditioner, water retainer in horticulture
- Absorbent media for safe disposal of liquid and solid effluents
- Diluent/carrier/filler material in Animal health products, Agro-chemicals, Veterinary formulations, Vitamin premixes, Pharmaceuticals, etc.
- Xylose - a sweetener

Figure 3 Corncobs

2.1.2 The production process of corncob powder

First, the corncobs transported by a scraper, then it put the corncobs into an even feeder, it connects to a conveyor which transport corncobs up and into the first crusher, where the corncobs are grinded roughly, then the output, the rough powder, is transported by the second conveyor to the second crusher, where the powder is processed from rough to fine. It can be noticed that, there is a tube connected to the crusher chamber, the dust and tiny corncob powder is blown by the warm and wet air from the chamber into a filtering system, which includes a decanter centrifugal filter, a pulse-jet bag powder collector and a 7.5 bar rotating compressor. The mixed powder is filtered first in the sleeve filter, where the dust passes the filter and download from the bottom of centrifuge, then the powder goes into the pulse-jet bag dust collector, the collector here acts as a powder collector instead of the dust, the corncobs powder is collected falls down to the conveyor and is transported back to the main line. There is a rotating air compressor to produce compressed air for the two filters, the decanter uses 1/8 and the pulse-jet bag powder collector uses the rest. Finally, the powder filtered from the dust join the powder out of the second crusher, and are lifted by a spiral elevator, then transported to the stock of finished powder by a conveyor.

The flow chart below indicates the production process:

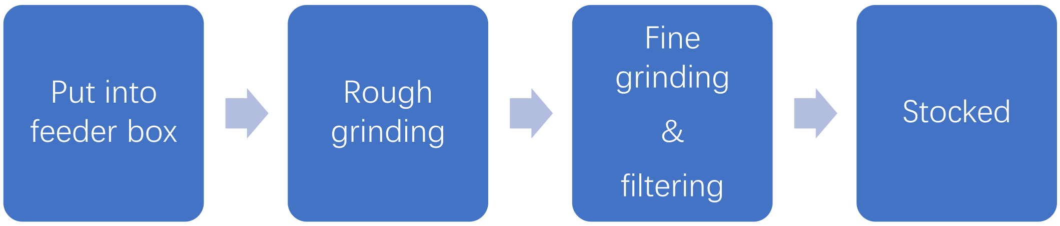

Figure 4 Production process

2.2 Production Devices

2.2.1 Even feeder

Figure 5 Even feeder

The even feeder is located at the head of the production line, its function is to provide a consistent, accurate material for the whole line. This type of feeder has an open even which is very convenient for scraper to unload the corncobs. It receives the corncobs from the scraper, then delivers them to the first crusher. In our case, we choose a double motor, eight spiral shafts even feeder, which can move the corncobs with the spiral shaft, and discharge corncobs on the conveyor from the bottom.

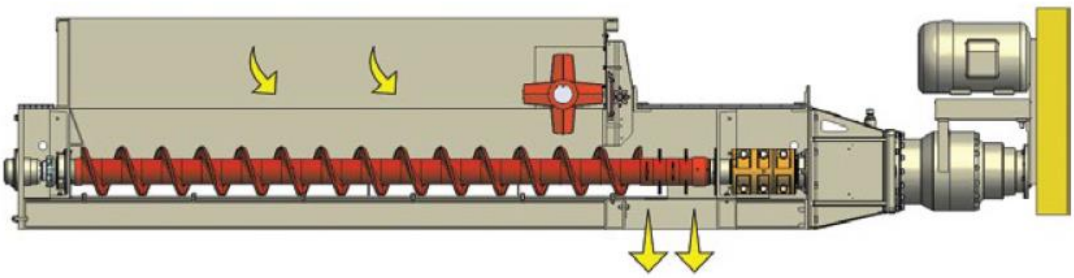

Figure 6 Working of the feeder

The technical data of feeder is below:

Type	Double motor 8 shafts
Power	2 AC motor, variable speed, 20kw totally

Loading operation	Front loading, rear discharge
Reducers	High torque planetary reducer
Rotation speed	0-40 RPM
Maximum throughput	170 m^3/h

The dimensions of the feeder are shown below:

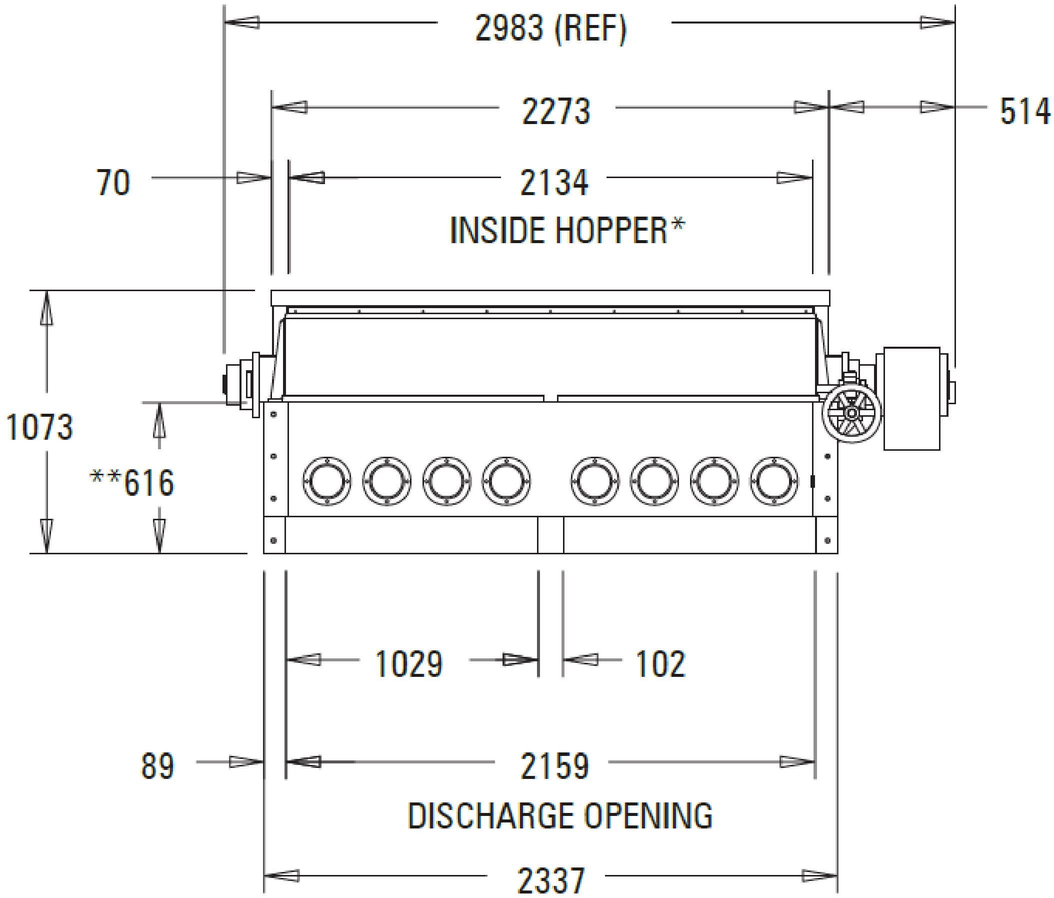

Figure 7 The dimensions of feeder

2.2.2 Primary crusher

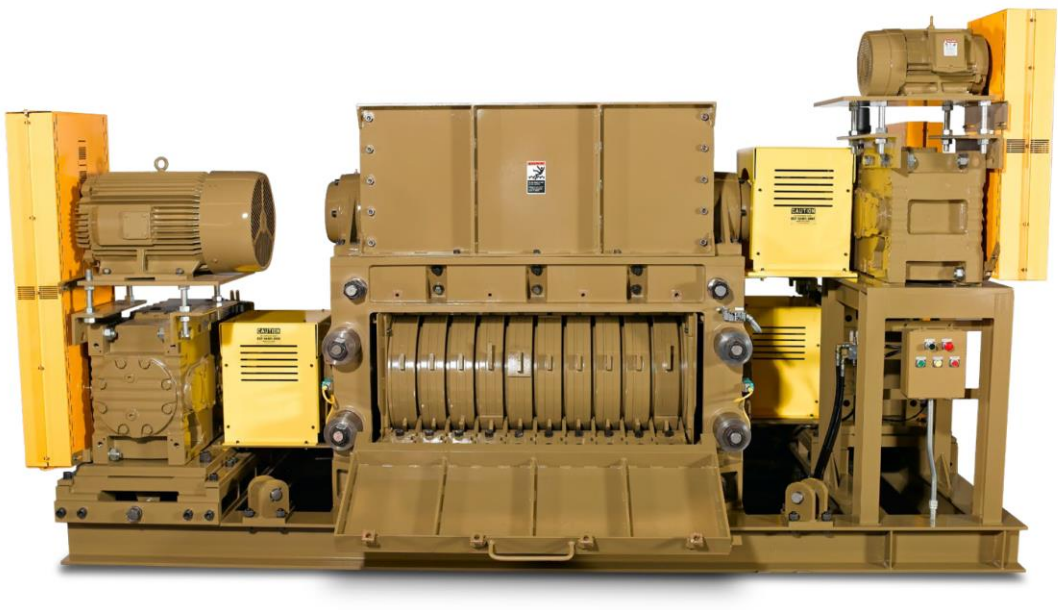

Figure 8 Primary roller crusher

The primary crusher is to roughly smash the corncobs into small pieces, it uses its roller with blades to crush the corncobs. And the size of output pieces can be adjustable by setting roll space between rollers. It has three rollers (slow, fast and feed) with 3 different driving motor.

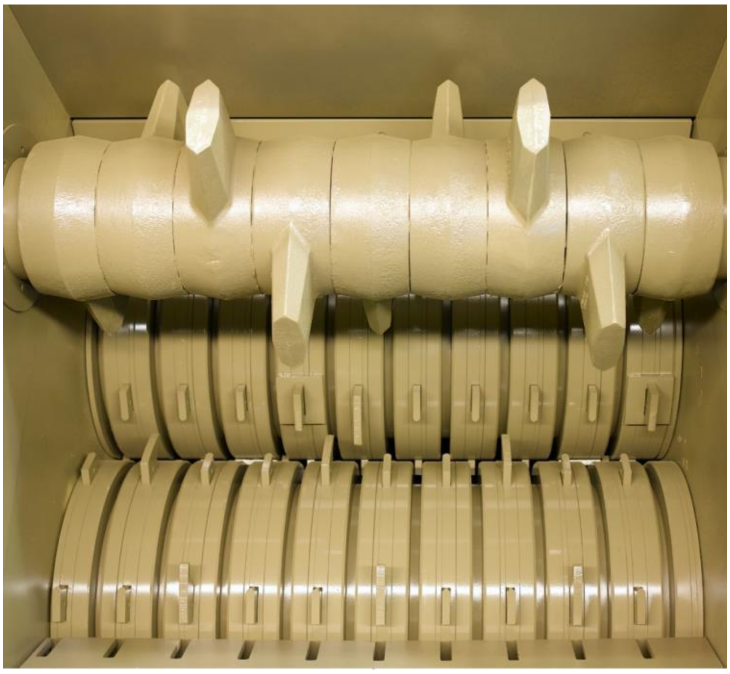

Figure 9 Rollers and blades

The technical data of the crusher is below:

Dimensions	L*W*H=2.2*2.4*4.5 (m)
Power	3 motors, 70kw in total
Rolling speed	Slow/fast/feed 48/50/15 RPM
Output size	Min. 25mm
Throughput	40 t/h

2.2.3 Secondary crusher

The secondary crusher is a hammer mill, which has blades on its two contrapositive rolls. It can crush the small pieces of corncobs into powder, then discharge from bottom of the device onto the conveyor.

Figure 10 Hammer mill

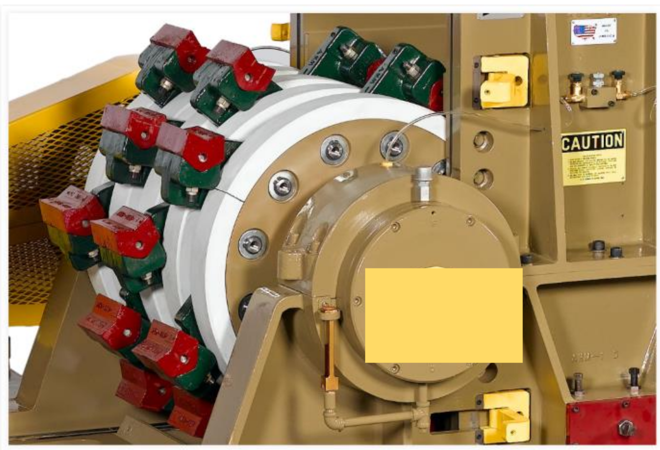

Figure 11 The blades of the hammer

The technical data of the crusher is below:

Type	Two rotors with hammer tips
Rotor speed	900 RPM
Motor	2 motors, 60kw, 1600RPM
Throughput	50 t/h

The dimensions are shown below:

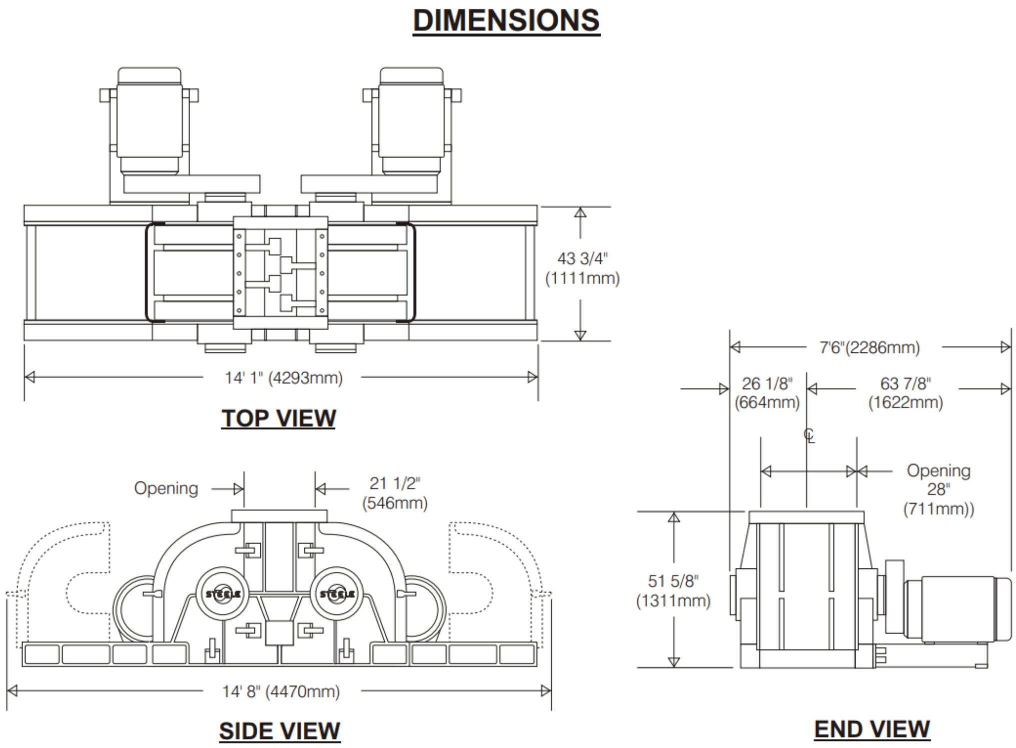

Figure 12 The dimensions of the crusher

2.2.4 Filtering devices

During the secondary crushing, there is some tiny corncobs powder mixed with dust blowing up in the crusher chamber. In order to take back this portion of powder, avoiding waste, we put a tube to connects the chamber to a filtering system, which filters the mixed dust to corncobs powder and collects back to the main production line. This system includes a sleeve filter, a pulse-jet bag dust collector and a rotating air compressor.

2.2.4.1 Sleeve filter

Figure 13 Sleeve filter

The sleeve filter is a device to separate the dust from the corncobs powder, there is a filter sleeve inside the centrifuge, the micro powder can pass through the filter while the dust remains inside the filter. Then the dust gathers and unloaded from the bottom of the centrifuge. And this progress is enhanced by the compressed air, which uses 1/8 of that from the compressor.

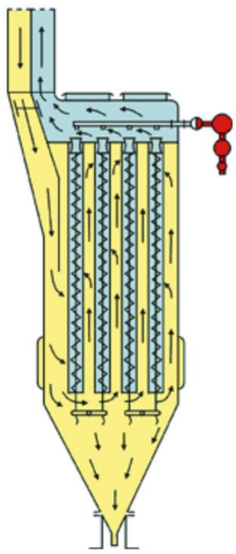

Figure 14 The structure of filter

The technical data of the filter is below:

Capacity	10 m^3
Dimensions	1 m in diameter, 3.5 m in height

2.2.4.2 Pulse-jet bag powder collector

Figure 15 Pulse-jet bag powder collector

This device is originally used to clean the air and control dust in industrial application, here we use this device to collect the corncobs powder from the filtered air from the sleeve filter. When the air containing the powder enters the chamber, the bigger powder will fall directly on the bottom of the collector, the smaller one will attach on the filter bag when the air flow out through the filter by a fan located on the top of the collector. When the quantity of the powder increases, the resistance of the flow rises, and when it exceeds the determined level, the inlet closed and pulse valves open, the compressed air blows in, shaking the filter bags to let the tiny powder dropping down, the process just lasts 0.1-0.2s. Finally, the bottom open and the collected powder is unloaded onto the conveyor and sent back to the main production line.

The technical data is below:

Flow	1320 m^3/h
Dimensions	L*W*H=2*1.5*5 m
Gas consumption	1 m^3/min
Power consumption	3 kw

2.2.4.3 Rotating compressor

Figure 16 Rotating compressor

We use a rotating air compressor to supply the compressed air we need.

The technical data is below:

Pressure	7.5 bar
Dimensions	L*W*H=1.9*1.4*1.5 m
Motor	37 kw
Free delivery air	3.3 m^3/h

2.2.5 Material handling equipment

2.2.5.1 Conveyor

Since we need to transport the powder instead of components, so it is not suitable to use traditional conveyor like belt conveyor, because the powder will attach to the belt and go inside the conveyor, damaging the mechanical structure. To this end, we use the powder screw conveyor, which is very common in agricultural area. The conveyor is like a long tube with a straight steel screw inside it. When the screw is rotating, the scraper on that will push the powder from one side to the other, without dropping powder out. We use 2 kw motor to drive it.

Figure 17 powder conveyor and its structure

2.2.5.2 Spiral elevator

Figure 18 Spiral elevator

In the final stage, there is a spiral elevator to lift the powder up to a conveyor and transports it to the powder stock. We use a 6m height elevator with a 5-kw motor.

2.2.5.3 Scraper

Figure 19 Scraper

In our case, we use a small size scraper, which is common in agricultural area.

The technical data is shown below:

Capacity	0.85 m^2
Fuel consumption	About 8L/h diesel

Chapter 3 Production hierarchical models

During the Industrial 4.0 era, we put forward a concept of ‘Digital Factory’ which uses digital technology for modeling, communications and to operate the manufacturing process. This arrangement of technology allows managers to configure, model, simulate, assess and evaluate items, procedures and system before the factory is constructed. The digital factory gives answers for configuration, design, screen and control of a production system. This becomes an indicator of informatization for a corporation. This technology is supported by the virtual simulation technology, on the other hand, the continuous development of automatic control and advanced sensor technology allow the fast improvement automation of the company. Therefore, the digital factory is the combination of both, that is, the digital factory is not the realization of the virtual simulation, neither the simple application of automation for the real factory, but a new mode of factory with the support of digital technology and cyber physics system.

Figure 20 Manufacturing in industry 4.0

In order to do the simulation of the virtual factory, we need to build a hierarchical model of production system, which includes many layers to describe different aspects of the production system.

These layers are:

- The 2D layout: devices position
- The 3D layout: occupied space
- The flow model: where material and fluid and energy arrive or depart
- The variables model: which variables we measure and control (the measuring system and the simulation system)
- The management model: to plan and forecast the production process
- The financial model: about costs and profits of the manufacturing system
- The social model: the impact of the manufacturing process on society and environment

To build a such model, the first thing is to analyze the requirement of the production system, like many other engineering project, this is based on the requirement of the company, so before we build the model, we need to know these requirements to avoid misunderstanding during the process. Usually, these requirements can be summarized as several questions:

- What does the model look like?
- What need to be simulated?
- What are the indicators we need to pay attention to?

In detailed, it can be divided into several steps:

First, fully understanding the technical scheme, including the production process, production devices, production layout, workers;

Second, clear definition of the object of the simulation. To build a model which can be adjustable to the real production, we need to know all the objects of the model for each single device, process. And we need to figure out the level of detail for each model according to the requirements;

Then, an explicit representation of the model. We need to show the model in the way that clearly express the production process, devices, layout, etc.

Finally, this model must be suitable to kinds of simulation software, like Flexsim, and by simulation, we can check the model according to the restrictions of the design, like space, time, human resource, devices, etc.

Below are different layers of the hierarchical model based on our production system.

3.1 2D model

First, we need a 2D model of the production system to indicate the layout of the production workshop.

Workshop layout refers to the overall arrangement of the basic positions of the workshop, auxiliary sections, production service departments, facilities, equipment, warehouses, passages, etc. The layout of the workshop is designed to make the most efficient use of the plant space. On the one hand, it is convenient for work and operation, and avoids overcrowding of production equipment. On the other hand, pay attention to ventilation, fire prevention and explosion prevention of the plant to ensure safe production.

The goals of the layout design are:

- 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/tools
  - Easy access to materials

- Avoid noise, set appropriate 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

Depending on the dimensions of the devices and the production process, we can draw the 2D blocks model of our production system with AutoCAD:

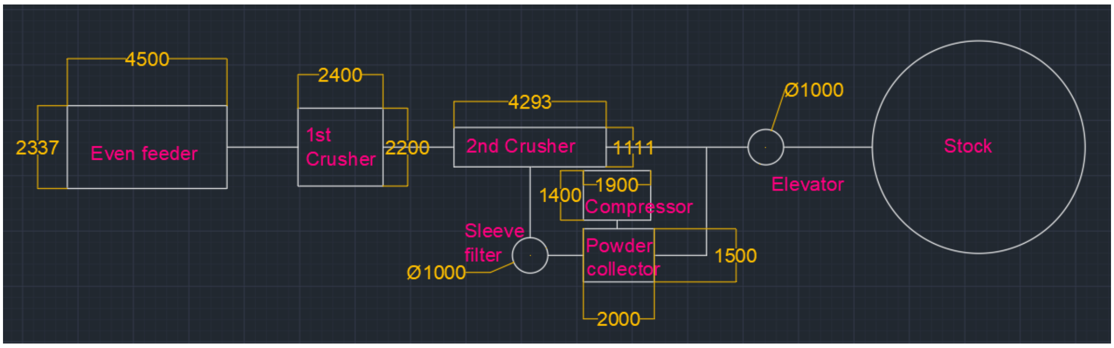

Figure 21 2D model

3.2 3D model

After concluding the 2D model, we can further develop the 3D model considering the height of the workshop to indicate the spatial layout.

The 3D block model considers the height restriction of the workshop, so it can show us not only the height of the production line but also give us an indicator to design other auxiliaries in the workshop like HVAC, lightning systems.

To build this model, we can also use the AutoCAD and directly based on the 2D model. Just extend the 2D blocks with the height of each production devices, we can get the 3D block model of the production line:

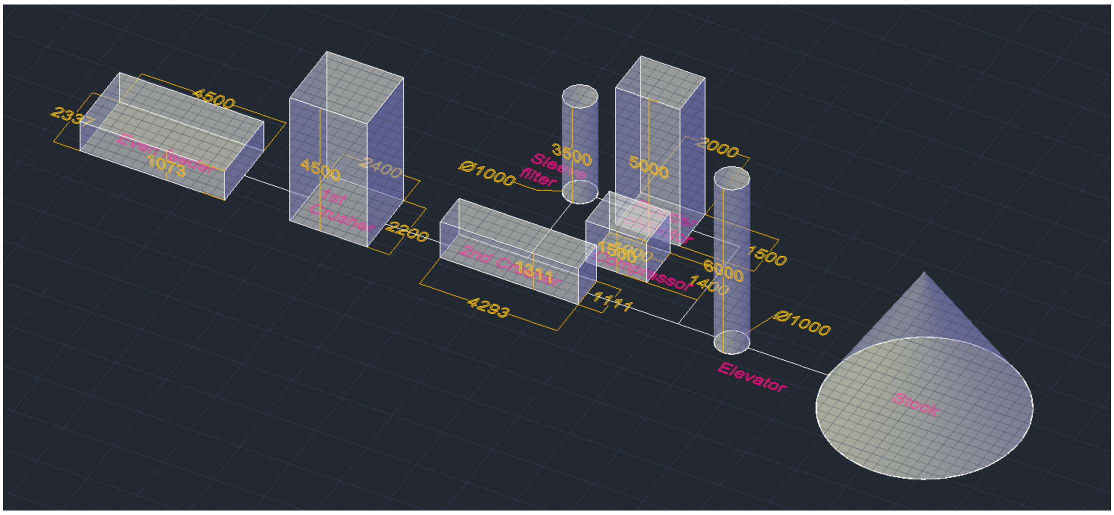

Figure 22 3D model

3.3 The flow model

The flow model, also called material flow, is the description of the transportation of raw materials, pre-fabricates, parts, components, integrated objects and final products as a flow of entities. The term applies mainly to advanced modeling of supply chain management.

Material flow analysis (MFA), also referred to as substance flow analysis (SFA), is an analytical method to quantify flows and stocks of materials or substances in a well-defined system. MFA is an important tool to study the bio-physical aspects of human activity on different spatial and temporal scales. It is considered a core method of industrial ecology or anthropogenic, urban, social and industrial metabolism. MFA is used to study material, substance, or product flows across different industrial sectors or within ecosystems. MFA can also be applied to a single industrial installation, for example, for tracking nutrient flows through a waste water treatment plant. When combined with an assessment of the costs associated with material flows this business-oriented application of MFA is called material flow cost accounting. MFA is an important tool to study the circular economy and to devise material flow management. Since the 1990s, the number of publications related to material flow analysis has grown steadily. Peer-reviewed journals that publish MFA-related work include the Journal of Industrial Ecology, Ecological Economics, Environmental Science and Technology, and Resources, Conservation, and Recycling.

In our case, the main process is the transformation of corncobs into powder, with the consumption of electricity, fuel and compressed air. So, the corncobs and these consumables are the input of the system, the corncobs powder is the output of the system. So, we can figure out and analyze the material flow according to the production process.

3.3.1 Raw materials

The input of the whole production progress are the corncobs, which are delivered by the scraper. We use dried corncobs in order of reducing loss through crushing, the density of which is about 200 kg/m^3 (because the shape of corncob is far from regular, so there are many gaps among a stock of corncobs, so the density of the corncobs is much less than the powder, which is about 800kg/m^3). The input flow of the corncob depends on the capacity of the even feeder, in our case, it is 170 m^3/h.`, we consider that we use 80% of its capacity, which is 136 m^3/h, so we think that the input of raw material is 136 m^3/h or 27.2 t/h.

3.3.2 energy consumption

During the production progress, the sources we consume are electricity, diesel and compressed air while the compressed air is provided by the compressor, it can be regarded as electricity consumption.

The electricity consumption is the sum of each devices (even feeder, crushers, conveyors and filtering system, except air compressor), and we consider that all the devices are working under rated power.

Regarding the diesel, it is the fuel of the scraper, according to our choice, for one scraper it has a capacity of 0.85 m^2 and fuel consumption of 8L/h. If we need the 136 m^2/h supplying of corncobs and we think that one scraper can finish one load & unload operation in 1min, so we need 136/60/0.85=2.67 scarpers, that is 3 scrapers, so the diesel consumption is 3*8=24 L/h.

The compressed air we use is for powder collector of 1 m^2/min and for sleeve filter is 1/8 of collector, so totally 1.25 m^2/h. Since the free delivery air of our compressor is 3.3 m^2/h under 37 kw, so we just actually use 1.25/3.3*37=14 kw power of the compressor.

3.3.3 The loss of each production stage

During the production stages, there are several stages can deduce losses of corncobs powder. For the even feeder, since the corncobs are not tiny so we can consider there is no loss in this stage. For the first crusher, because its output is relatively bigger than the final powder, so the loss is little, we think it is 1%. Regarding the secondary crusher, since it produces fine powder which is easily attach and hide inside the chamber so there can be a bit more loss, we consider that it is 2%, and 20% powder enters into filtering system mixed with dust. Because the efficiency of powder collector is 99% so we think that the powder loss of the total filtering system is 1%. About the conveyors, we just consider the loss of elevator which is 1%.

3.3.4 Material flow

According to the consideration above, we can draw a material flow diagram:

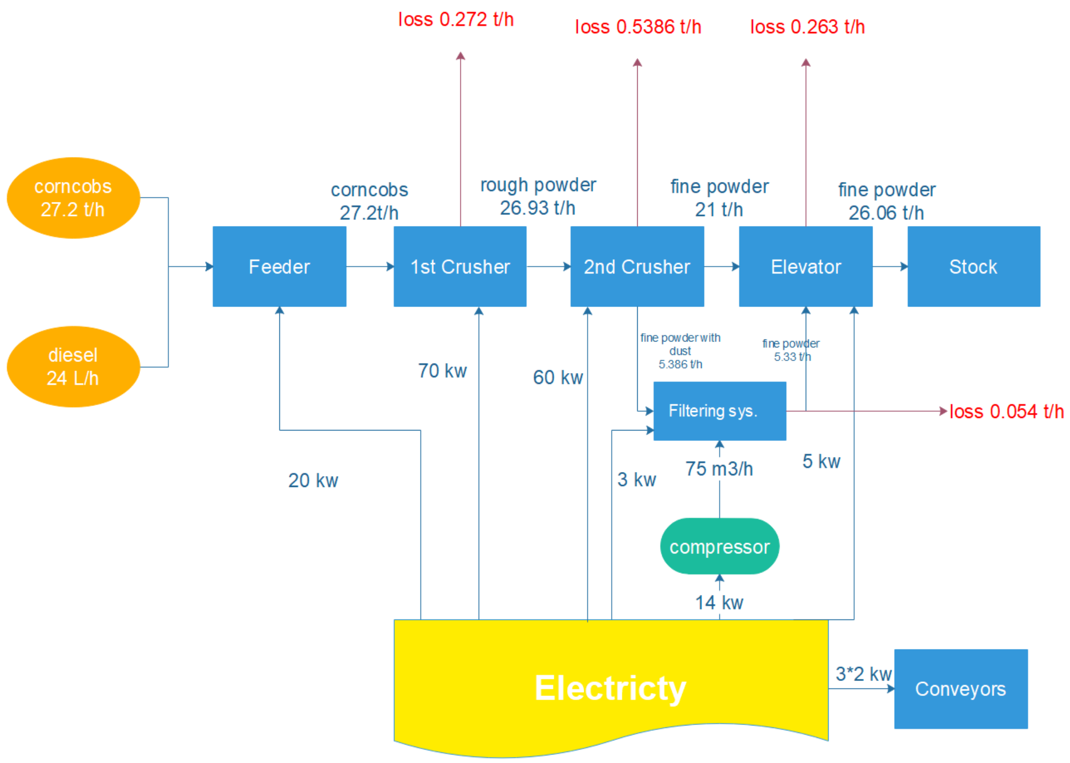

Figure 23 Material flow diagram

As can be seen from the diagram that, the corncobs and diesel are the input which enter the production system, and there is always loss during each procedure, these are the materials that depart from the production system. On the other hand, the working of the devices needs the supplement of electricity as well as the conveyors.

The whole production process consumes 24 L/h diesel and 178 kw electrical power to transform 27.2 t/h corncobs to 26.06 t/h corncobs powder, the efficiency is 26.06/27.2*100%=95.5%.

3.4 The variables model

Manufacturing device is the fundamental unit of the manufacturing process for a manufacturing company. The performance and operating state directly affect the manufacturing level and manufacturing cost of the manufacturing company. Therefore, it is necessary to evaluate the performance of the manufacturing device and track its operating state, dealing manufacturing problems timely in any emergencies to ensure reliability and efficiency of the manufacturing process.

We can use kinds of variables of a device to evaluate the performance of the device, as well as the whole production system.

The ISO 22400 standard "Automation systems and integration —Key Performance Indicators (KPIs) for manufacturing operations management", provides an overview of the concepts, the terminology and the methods to describe and to exchange KPIs for the purpose of managing manufacturing operations. To evaluate the performance of manufacturing operations, a total of 34 KPIs are presented in its latest update – ISO 22400-2:2014. In the standards, the KPIs are described by means of their formula, corresponding elements, unit of measure, timing and other characteristics. The ISO 22400 aims at defining the most important and generally used measures for the manufacturing industry, and therefore it has been recognized for its potential contribution on manufacturing operations management.

In order to evaluate the performance of our manufacturing device, we need to build a general variables model of a manufacturing device based on ISO 22400 standard. This model should include all the variables needed in ISO 22400 and, if necessary, add more variables specifically to our device.

3.4.1 Variables in ISO standard

The variables in ISO 22400 standard can be divided into 4 categories which are time, logistical, quality and energy.

- **Time variables:**

  For device:

  - Planned order execution time (POET): the planned time for executing an order.
  - Planned operation time (POT): the planned time in which a device can be used. The operation time is a scheduled time.
  - Planned unit setup time (PUST): the planned time for the setup of a work unit for an order.
  - Actual unit setup time (AUST): the actual time consumed for the preparation of an order at a device.
  - Actual transport time (ATT): the actual time required for transport between devices.
  - Actual unit processing time (AUPT): the actual production time plus the actual unit setup time.
  - Actual unit busy time (AUBT): the actual unit processing time plus the actual unit delay time.
  - Actual order execution time (AOET): the time from the start of the order until the time of the completion of the order.
  - Time between failures (TBF) the actual unit busy time (AUBT) between two consecutive failures of a work unit including setup time, production time and repair time related to the orders being processed and without delay times.
  - Time to repair (TTR): the actual time during which a device is unavailable due to a failure.
  - Time to failure (TTF): the time between failures minus the time to repair.
  - Failure event count (FE) the count over a specified time interval of the terminations of the ability for a device to perform a required operation.
  - Corrective maintenance time (CMT): the part of the maintenance time during which corrective maintenance is performed on a device, including technical delays and logistic delays inherent in corrective maintenance.
  - Preventive maintenance time (PMT): the preventive maintenance time is the

part of the maintenance time during which preventive maintenance is performed on a device, including technical delays and logistic delays inherent in preventive maintenance.

(2) Logistical variables

- Planned order quantity (POQ): the planned order quantity is the planned quantity of products for a production order (lot size, production order quantity).
- Scrap quantity (SQ): the scrap quantity is the produced quantity that did not meet requirements and either to be scrapped of recycled.
- Planned scrap quantity (PSQ): the planned scrap quantity the amount of process-related scrap that is expected when manufacturing the product (e.g. at the start or ramp-up phases of the manufacturing systems).
- Good quantity (GQ): the good quantity is the produced quantity that meets quality requirement.
- Rework quantity (RQ): the rework quantity: the rework quantity is the quantity that fails to meet the quality requirement, but these requirements can be met by subsequent work.
- Produced quantity (PQ): the produced quantity is that a device has produced in relation to a production order.
- Raw materials (RM): the raw materials are that are changed into finished goods through the production.
- Raw materials inventory (RMI): the raw materials inventory is the inventory of materials that are changed into intermediates or finished goods through production.
- Finished goods inventory (FGI): the finished goods inventory is the amount of acceptable quantity which can be delivered.
- Consumable inventory (CI): the consumable inventory is the material which is transformed in quantity or quality during the production process and which is no longer available for use in production operations.

- Consumable material (CM): the consumed material is the summed quantity of materials consumed by a process.
- Integrated good quantity (IGQ): the integrated good quantity is the summed product count or quantity resulting from a multi-product process used in KPI calculations instead of GQ.
- Production loss (PL): the production loss shall be the quantity lost during production, calculated as output minus input.
- Storage and transportation loss (STL): the storage and transportation loss are the quantity lost during storage and transportation.
- Other loss (OL): other loss is the quantity lost due to extraordinary incidents.
- Equipment production capacity (EPC): equipment production capacity is the maximum production quantity of production equipment.

(3) Quality elements:

- Good part (GP): a good part is the count of individual identifiable parts, e.g. serialization, which meets the quality requirements.
- Inspected part (IP) an inspected part is the count of individual identifiable parts, e.g. by serialization, which was tested against the quality requirements.
- Upper specification limit (USL): an upper specification limit is a value below which performance of a product or process is acceptable. It represents the maximum acceptable value of a variable.
- Lower specification limit (LSL): a lower specification limit is a value above which performance of a product or process is acceptable. It represents the minimum acceptable value of variable.
- Arithmetic average ($\bar{x}$): if, in a series of n measurements, each measured value $x_1, \ldots, x_2, \ldots, x_n$ was measured independently based on repetition conditions, then $\bar{x}$ represents the arithmetic average value from these n individual values.
- Average of average values ($\bar{\bar{x}}$): $\bar{\bar{x}}$ is calculated from the average of single sample average values.

- Estimated deviation ($\hat{\sigma}$): it is calculated by the average value of the standard deviation from a sequence of samples with constant random inspection size, multiplied by a confidence factor depending on the random inspection size of the standard deviations.
- Standard deviation (σ): it is a measure for the dispersion of measured values around its average value and is determined from the square root of the variance.
- Variance (σ^2): the variance is a measure which describes how strongly a measured variable (characteristic) strews. It is calculated as the distances of the measured values from the average value are squared, summed up and divided by the number of measured values.

(4) Energy elements:

- Actual direct energy consumption (ADEC): the actual direct energy consumption is the measured direct energy consumption per device and during actual unit busy time.
- Planned direct energy consumption per item (PDEI): the planned direct energy consumption is the planned energy consumption in average for producing one product item.
- Time period: a time period is the time during which device is in a specific state. With each change of stating a new time period always begins.

3.4.2 Key performance indicator

Key performance indicator (KPI) is that by setting, sampling, calculating, and analyzing the output, input, and important parameters of the specific process to obtain the relative data, which is a quantitative management indicator that measures performance of the process. The performance includes business process performance and production process performance; while the key performance is an important goal or success factor to evaluate business processes and production processes. Key performance indicator evaluation is a method and theory that comprehensively applies multiple disciplines and establishes corresponding key performance indicator evaluations for evaluating objectives.

The idea of key performance indicator evaluation comes from the performance management in management theory, which is mainly used for guiding, and evaluating the human resources and business operations. In the early 20th century, in order to assess the relationship between the investment and income of the enterprise, DuPont's founder Pierre S. DuPont proposed an analysis method which combines several ratios used to evaluate business efficiency and financial status to build a complete indicator evaluation system.

The term KPI first appeared in the British construction industry. In order to facilitate the owners, contractors, suppliers and other project participants to accurately and objectively evaluate each other's performance, the relevant research institutions of the UK formulated the construction industry, and since then, KPI research has been widely applied in various fields.

The evaluation of key performance indicators not only focuses on the macro and overall economic benefits of enterprises, but also deeply analyzes the business process and production status of enterprises. The purpose, object, time scale, subject and result of the evaluation should be considered and analyzed when the key performance index is used to evaluate, so to achieve the objective of targeting the target.

1) Purpose of evaluation

The purpose of key performance indicator evaluation is the core problem of using key performance indicator to evaluate. It means that to select the scope of key performance indicators and establish the positioning of key performance indicators evaluation system, the specific KPI evaluation process is based on this implementation. Enterprises need to clear evaluation purpose according to their own production characteristics and business scope, making the key performance index evaluation play a critical role.

2) Evaluation object

The object of evaluation is the significant point which enterprises focus on in the evaluation with KPI. Under the premise of determining the evaluation object, selecting the appropriate evaluation index and evaluation standard, and conducting targeted KPI evaluation is very important. At the same time, according to the characteristics of the evaluation object, choose the KPI from many evaluation indicators to conduct efficient evaluation.

3) The time scale of the evaluation

Due to the different characteristics of the evaluation objects, the evaluation time scale used by different KPIs is also different. For macro and stable KPIs, a long-time scale is often adopted; And for specific, real-time ones, a short-time scale is often used.

4) Subject of evaluation

The main body of evaluation is the user of the result of KPI evaluation, so the KPIs used are different. To the production equipment used in the production process of the enterprise, for example, production managers focus on the production cost and quality of production equipment, and information managers focus on production equipment backup information integration and timeliness, while maintenance managers pay more attention to the failure rate and maintenance cycle of production equipment. Therefore, it is necessary to clarify the evaluation subject and ensure the effectiveness and objectivity of the evaluation of key performance indicators.

5) Evaluation result

How to combine the results of key performance indicator evaluation with the management objectives of the enterprise to promote the enterprise's business process and the optimization of production process is also an important aspect to be considered in the KPI evaluation. The evaluation result of KPI can play the role of feedback to the operation and production management of the enterprise. Through comparing the evaluation result with the set basic value, detect and monitor the rationality of enterprise business process and production process. This provides the guidance for business process adjustment and production process improvement.

Based on the ISO 22400, we can clarify the KPIs into three different categories, which are production, quality and maintenance.

3.4.2.1 Production KPIs

When we are concerned about the production issues and at the single device level, we can have KPIs below:

- **Worker efficiency (WE):** it considers the relationship between the actual personnel work time (APWT) related to production orders and the actual personnel attendance time (APAT) of the employee:

$$WE=APWT/APAT$$

- **Availability (A):** the portion of the time that the device is available, i.e. the actual cycle time multiplies the quantity (Q) among the planned working time:

$$A=(AUPT-AUST)/POT *100\%$$

- **Allocation efficiency (AE):** the actual usage and availability of planned capacity of machine, which is the actual working time over the planned working time:

$$AE= AUBT/POT*100\%$$

- **Technical efficiency (TE):** it is the relationship between the actual production time (APT) and the sum of the actual production time (APT) and the actual unit delay time (ADET) which includes the delays and malfunction–caused interruptions:

$$TE=APT/(APT+ADET) *100\%$$

- **Effectiveness (E):** it represents the relationship between the planned target cycle and the actual cycle expressed as the planned runtime per item (PRI) multiplied by the produced quantity (PQ) divided by the actual production time (APT):

$$E=PRI*PQ/APT$$

- **Utilization efficiency (UE)**: The productivity of a machine, measured by the ratio between the AUPT, AUST and the AUBT. If the actual unit delay time and setup time are high, the UE will be low:

$$UE=(AUPT-AUST)/AUBT*100\%$$

- **Machine capability index (MCI):** it is the relationship between the dispersion of a process and the specification limits. The method compares the range between the specification limits (USL, LSL) and the 6σ dispersion of a series of measurements for a specific characteristic:

$$MCI=(USL-LSL)/\ (6*\sigma)$$

- **Critical machine capability index (CMCI):** it is the relationship between the dispersion of a process and the upper or lower specification limit (USL, LSL) and its averages ($\bar{x}$):

$$CMCI=Min\ [(USL-\bar{x})/\ (3*\sigma),\ (\bar{x}-LSL)/\ (3*\sigma)]$$

- **Process capability index (PCI):** is the relationship between the dispersion of a process and the specification limits:

$$PCI=(USL-LSL)/\ (6*\hat{\sigma})$$

- **Critical process capability index (PCI):** it is the relationship between the dispersion of a process and the upper or lower specification limit (USL, LSL) and its average of the averages ($\bar{\bar{x}}$):

$$CMCI=Min\ [(USL-\bar{\bar{x}})/\ (3*\hat{\sigma}),\ (\bar{\bar{x}}-LSL)/\ (3*\hat{\sigma})]$$

- **Setup ratio (SeR)**: The relative loss of value adding opportunity for a machine due to setup, measured by the ratio of AUST to AUPT. The complementary proportion is the APT.

  SeR=AUST/AUPT*100%

Regard to the whole production line, these KPIs can be applicated:

- **Allocation ratio (AR):** The percentage of actual busy time of all machines (AUBT) among the AOET of a production order. The complementary proportion describes the ratio of actual queuing and transportation time.

  AR=AUBT/AOET*100%

- **Production process ratio (PR):** The efficiency of production when considering the actual unit setup time, delay time, transportation time, and queuing time. It is the ratio between the APT over all work units and work centers involved in a production order and the whole throughput time of a production order which is the AOET.

  PR=APT/AOET*100%

- **Equipment load ratio (ELR):** it considers the produced quantity (PQ) in relation to the equipment production capacity (EPC):

  ELR=PQ/EPC

- **Throughput rate (TR)**: The process performance indicator in terms of produced good part quantity of an order (GQ+RQ) if the reworked parts are in good quality) and the actual execution time (AOET), measured by the ratio of PQ and

AOET. Since PQ is a quantity related metric, throughput rate also belongs to the quantity category as well.

$$TR=(GQ+RQ)/AOET*100\%$$

- **Overall equipment effectiveness index (OEE):** it represents the availability, effectiveness and quality ratio of a work unit KPIs integrated in a single indicator:

$$OEE=A*E*QR$$

3.4.2.2 Quality KPIs

Below are some critical KPIs which evaluate the quality of the production system:

- **Quality ratio (QR):** The quality ratio is the relationship between the good quantity (GQ) and the produced quantity (PQ):

$$QR=GQ/PQ*100\%$$

- **Actual to planned scrap ratio (APSR):** the scrap quantity (SQ) divided by the planned scrap quantity (PSQ) indicated how much scrap was actually produced compared with the expected (planned) value:

$$APSR=SQ/PSQ$$

- **Rework ratio (RR):** The percentage of RQ among PQ.

$$RR=RQ/PQ*100\%$$

- **Quality buy rate (QBR):** The overall percentage of good quality parts after reworks.

$$QBR=(GQ+RQ)/PQ*100\%$$

- **Finished goods ratio (FGR):** it is the ratio of the good quantity produced (GQ) to the consumed material:

$$FGR=GQ/ CM$$

- **First pass yield (FPY):** it designates the percentage of products, which full fill the quality requirements in the first process run without reworks (good parts). It is expressed as the ratio between good parts (GP) and inspected parts (IP).

FPY=GP/IP

- **Inventory turns (IT):** it is specified as the ratio of the throughput (TH) to average inventory. It is commonly used to measure the efficiency of inventory, and represents the average number of times the inventory stock is replenished or turned over:

IT=TH/average inventory

- **Integrated goods ratio (IGR):** it is the relationship of the produced quantity of integrated goods (IGQ) to the consumed material (CM):

IGR=IGQ/CM

- **Production loss ratio (PLR):** it is the relationship of quantity lost during production to the consumed material (QM):

PLR= PL/CM

- **Storage and transportation loss ratio (STLR):** it is the relationship of the quantity of loss during storage and transportation (STL) to the consumed material (CM):

STLR=STL/CM

- **Other loss ratio (OLR):** it is the relationship of quantity lost not related to production, storage and transportation (OL) to the consumed material (QM):

OLR= OL/CM

3.4.2.2 Maintenance KPIs

The maintenance KPIs refer to repair and maintenance issues of the production system. By averaging all the repair time and operation time, some important KPIs of maintenance are below:

- **Corrective maintenance ratio (CMR):** it considers the corrective maintenance time (CMT) in relation to the total maintenance expressed as the sum of corrective maintenance time (CMT) and planned maintenance time (PMT):

$$CMR=CMT/\ (CMT+PMT)$$

- **Comprehensive energy consumption (CEC):** it is the ratio between all the energy consumed in a production cycle (e) and the production quantity (PQ):

$$CEC=e/PQ$$

- **Direct energy consumption effectiveness (DECE):** it represents the relation of the planned direct energy consumption per item (PDEI) multiplied by the produced quantity (PQ) to the actual direct energy consumption (ADEC):

$$DECE=PDEI*PQ/ADEC*100\%$$

- **Direct net energy consumption effectiveness (DNECE):** it represents the relation of the planned direct energy consumption per item (PDEI) multiplied by the good quantity (GQ) to the actual direct energy consumption (ADEC):

$$DNECE=PDEI*GQ/ADEC*100\%$$

- **Direct energy efficiency (DEE):** it shows the direct energy consumption (ADEC) per production item of the produced quantity (PQ):

$$DEE= ADEC/PQ$$

- **Direct net energy efficiency (DNEE):** it shows the direct energy consumption (ADEC) per production item of the good quantity (GQ):

$$DNEE = ADEC/GQ$$

- **Mean time to failure (MTTF):** the average time during a long period that the device can work during which the start of the last repair to the new failure.

- **Mean time to repair (MTTR):** the average time during a long period that the device is under repairing and unable to work

- **Mean operation time between failures:** it is the sum of MTTR and MTTF

3.4.3 Diagram of variables model

We can build a variables model with the analysis above, now we can present this model by the way of diagram, let's consider for a single production device (R_a, R_d represent the arrivals and departures of this device):

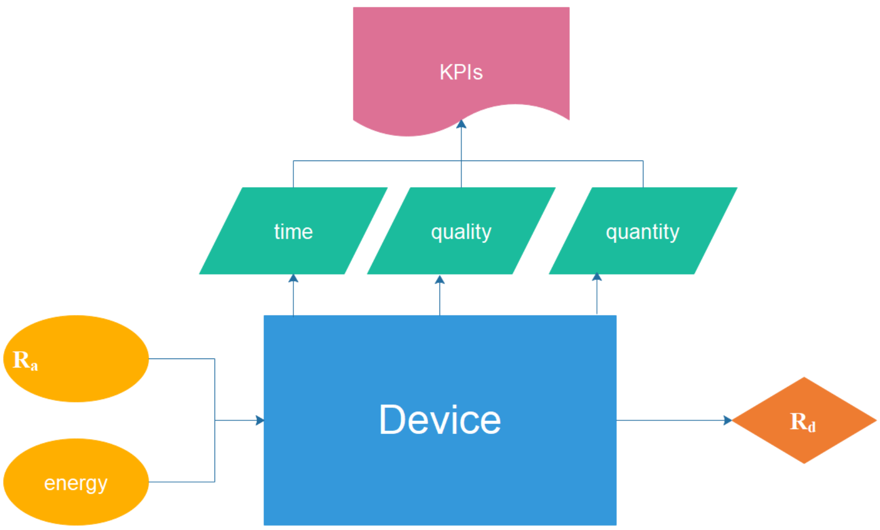

Figure 24 Diagram of variables model

3.5 The management model

Nowadays, the market competition and diversity of market demand are increasing, it is necessary for a company to carefully plan the production to reduce the inventory level in a limited amount and a short lead time while enough to meet the market demand.
The management model of the production system refers to fully planning the production process, which includes order management, production scheduling, inventory management, etc.

3.5.1 Order management

Order management system (OMS) is a part of the logistics management system. Through the management and tracking of orders issued by customers, the progress and completion of orders are dynamically mastered to improve the operational efficiency in the logistics process, so to save operation time and operational cost and improve the market competitiveness of logistics. The main function of the order management system is to provide users with integrated one-stop supply chain services through unified orders. Order management system is an indispensable part of logistics management chain, through the order management and distribution, warehouse management and transportation management organic union, stable effective logistics management in each link, give full play to the role, the warehousing, transportation, order as an organic whole, meet the needs of logistics information system. Order management is to manage, query, modify, print and other functions of various orders issued by the merchant, and meanwhile feedback the information processed by the business department to the merchant.
The order management system generally includes order processing, order confirmation, order status management (including cancellation, payment, delivery and other states, as well as order delivery and order query) and so on.
Below are some basic functions:

- **Order management** the system can realize single and batch orders, order management and inventory management, and the next order when the stock warning and prompt function, order management and customer management at the same time connected, can query the history of orders and order execution.

- **Distributor management** with emphasis on the enterprise's marketing channel construction, planning the information flow, logistics and cash flow in the supply chain system, strengthen the close cooperation between enterprises and vendors, and internal business process through a distributor specification to improve the resource management ability, at the same time to provide customers a full range of sales and service experience.
- **Order Fulfillment** The filled-out order form is sent to the warehouse responsible for the inventory that will fulfill the purchase. In the warehouse, inventory is monitored and the continuous supply from vendors is recorded. If inventory runs out unexpectedly by a large purchase order, warehouse managers will place an order to the purchasing department to place an order to vendors. If the business manufactures the goods, the warehouse notifies production of low or depleted inventory.

3.5.2 Production scheduling

After receiving the order and transfer it into the production plan, we need to do the production scheduling. It means that to arrange, control and optimize production work and workloads within the production system. It includes plan of production process, human resource, purchase raw materials and devices resource.

It has a significant effect on the productivity of the production system. In manufacturing, the purpose of scheduling is to minimize the production time and costs, by telling a production facility when to make, with which staff, and on which equipment. Production scheduling aims to maximize the efficiency of the operation and reduce costs.

- The benefits of production scheduling include:

- Process change-over reduction
- Inventory reduction, leveling
- Reduced scheduling effort
- Increased production efficiency
- Labor load leveling
- Accurate delivery date quotes
- Real time information

3.5.3 Inventory management

The inventory cost is a nonnegligible part of the finance of the company, it includes the procurement and transportation cost of the goods, the storage cost which contains the capital interest, material handling and human resource, investment amortizations, maintenance and shrinkage.

Therefore, we must carefully manage the inventory level to: reduce the demand uncertainty to keep a safety stock level, and to separate different operations phases, which is the way to allow sourcing, making and delivery to work at different rates and allows the different phases to be "asynchronous" and absorbs upstream variations.

The main thing should be decided is:

- **Replenishment policy**: how much and when to order

  Impacts on:

  -Stock carrying costs

  -Setup/order emission costs

  -Stock out / downstream service costs

  Constraints:

  -Production capacity and flexibility of upstream production level

  -Physical space limit of warehouses.

- **Control level**: the detail and the frequency of

  -control of the stock level of each item

Impacts on:

-Cost of control

-Constraints:

-Availability of resources to perform the controls (people, computers, ...).

3.6 The financial model

When talking about the financial model of the company, the first thing we need to consider is the cost.

Cost=Price - Profit

Where, the price is mainly due to the market, every company operate in a competitive market and the price competition is very significant for the competition among companies. The customer will not pay more price for the same performance of the service or product.

The profit is defined by the company according to the marketing strategy and positioning.

So, what the company should pay more attention to is the cost, which is controllable and directly affects the competitiveness of the company. By minimize the cost, the company can maximize the profit at the same price as competitors or minimize the price having the same profit as competitors.

As general definition, cost is the sum of monetary values of resources, goods, and services consumed by a Company to produce products sold and services rendered.

It can be classified by several criteria:

1) Volumes

- **Variable cost:** The cost that is directly proportional to volume of products produced
- **Fixed cost:** It does not change with volume variation of product produced
- **Semi variable cost** could be:
  Sum of a fixed plus a variable part or fixed within certain productive range with no correlation with production volume, but could be change with level of activity (e.g. Step correlation)

2) Attribution criteria

- **Direct cost** is directly attributable to the product or service and it is easily measurable as resource consumed per relative unit cost of the resource. Direct cost analysis allows the monitoring of the impact, on cost base, of resource required to produce that product.

- **Indirect cost** is not directly attributable to the product in objective way. Indirect costs are amounts spent or necessary to deliver the service or the product, but not exclusively related to the specific product/service. For this reason, indirect cost is associate to the product trough criteria for allocation.

3) Observation criteria

- **Specific costs** refer specifically and exclusively to the object observed. These costs, variable or fixed, are associated to productive factors consumed to produce a specific object (product, services, processing phase). Specific costs
for a product would not be sustained if the product/service is no more produced.
For example, specific cost could be, the depreciation of technical resource used by a specific department within the company. Referring to the product as object observed, can be classified as specific the cost for tools dedicated for its production (i.e. dies, check figures).

- **Common costs** are not associate at one object observed. These costs can be associated to the object observed only in an indirect and not univocal way using assumption, criteria and subjective base of attribution. Some examples of common costs are cost of personnel of IT, cost of managing warehouse common to all products, administrative, commercial, marketing expenditure
Referring to the product as object observed, can be classified as common the cost of machine used to process the product (e.g. press, DEA)

3.6.1 Cost analysis of the production system

To analyze the cost of our production system, we need to build a cost model. For a production system, we can divide the total cost into three categories: bill of material (BOM), bill of process (BOP) and mark-up.

3.6.1.1 Bill of material

Usually, the bill of material means the design frame of the product. It can be a single part or a complex part, assembled part or a system. It includes raw materials and purchased part (in case of manufacturing of an assembled product/system where subcomponents are bought from other manufacturers).

In our case, we just have the raw materials-corncobs, so the BOM of our production system is the cost of corncobs. It can be noticed that, the cost of raw material is not just the price of the material itself, but include many aspects:

- Base cost due to market drivers
- Transportation cost
- Costs for non-standard size, format
- Costs for quality certification
- Costs for warranty/insurance
- Mark-ups of raw material provider

However, material storage, inventory carrying costs and in-plant transportation are not included in raw material cost. These costs are charged on final product cost.

3.6.1.2 Bill of process

Bill of process refers to the cost during the process procedure, it includes direct labor, indirect labor and machine cost.

1) **Labor** is that all the operative human resource related to the manufacturing of the product, it can be categorized as two part: direct labor cost and indirect labor cost.
   - **Direct:** The labor of performing, either by hand or machine, manufacturing operations which further the physical progress of a component allocated to a specific part, operation or process. Direct labor is a value-added contributor to part cost.

The cost for direct labor per hour is below:

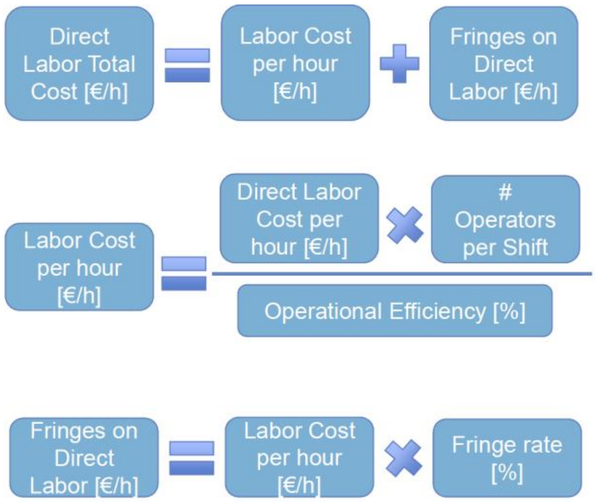

Figure 25 Direct labor cost

- **Indirect:** Represents all salaried and hourly labor, performing auxiliary work in connection with product manufacturing. Indirect labor is often categorized as a function, then determined as proportional relation to the absolute number of direct labor resource for a value-add manufacturing process.

The calculation of this per hour is shown below:

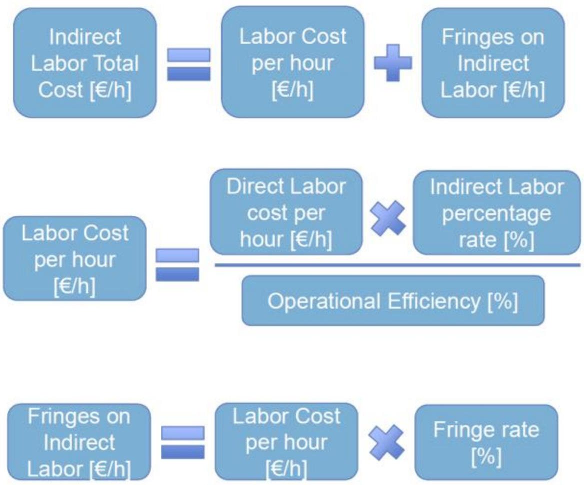

Figure 26 Indirect labor cost

2) **Machine cost:** The process of transforming a product can be split in single phases of production process. Each phase can be represented as a cost center, aggregating the resources required in terms of direct labor cost, indirect labor cost, and machine cost.

- **Machine hourly cost** is the result of all that expenditures, in terms of resource absorbed by the production system during the transformation process. To calculation this, we need to figure out some terms first.

- **Net Annual Operating Hours** represent the time available per year to run the productions. It is derived from the gross hours per years adjusted for the inefficiencies of the process due to many factors such as machine downtime, non-tag relief work patterns, or non-buffer in-process delays

$$Net\ Annual\ Operating\ Hours = Gross\ Annual\ Operating\ Hours * Operational\ Efficiency$$

- **Gross Annual Operating Hours per Year** are calculated as product of the hours per shift times, the number of production shifts per day times, the total number of available production days per year.

  Hours per shift represents the total number of daily hours per shift the value-add direct labor personnel are required to operate the selected machinery in a given value-add operation. The value is dependent upon location and it represents a fully utilized and volume dedicated production process.

  Shifts per Day: This field represents the total number of daily production work shifts required to operate the selected machinery in a given value-add operation. The number of shifts moves from one to three according to productive scenario (low volume vs high volume production)

  Production Days per Year: The value represents the total number of scheduled productions workdays per year and may vary significantly by country or region. It includes recognizing industry holidays, shutdowns and BEW programs.

- **Operational Efficiency [%]**: Operational Efficiency can be defined as the percentage of productive machine time that can be expected in a given operation that is operating in an optimal in-control process. This is sometimes referred to as "uptime" or the "full utilization" rate. However, this percentage is dependent on location & technology

- **Capitalization cost [€/h]:** is the rate that covers the machinery capital and the cost for equipment normal wear and tear, deterioration, or obsolescence. Those values are calculated over a pre-determined useful machine life (not always equal to the program duration/vehicle lifecycle).
  The hourly capitalization expense included in the burden calculation is based on the straight-line capitalization method and is:

$$Capitalization\ Cost = \frac{Machine\ \&\ Installation\ Cost - Machine\ Residual\ Value}{Gross\ Annual\ Operating\ Hours * Machine\ Usefull\ Life\ in\ Years * Operational\ Efficiency\ \%}$$

Where:

Machine and Installation Cost represents a new machine acquisition cost, including shipping and installation expenses for a required operation. The value is used in the calculation of all machine hourly capitalization rate and interest cost.

Machine Useful Life (years) is the estimated useful life of the machine equipment. Machine useful life is the basis for calculating the allowable annual or hourly capitalization expense as part of the machine hourly run rate.

Machine Residual Value is estimated cash recovery expected upon disposal of equipment at the end of its useful life stated as a percentage of the machine acquisition and installation cost. This value is subtracted from the machine acquisition and installation cost to determine the net machine investment cost that will be capitalized over the machine's useful life.

Used machine market is used as reference for machine residual value.

- **Interest cost [€/h]:** This is the external financing charge due to capital spent to acquire machinery and equipment.

  We assume that the machine and installation costs are financed over the machine's useful life (different from the specific program duration) at a predetermined financing interest rate.

  The difference between the amount borrowed initially and the total amount repaid is the total interest cost. These interest charges are then recalculated over the estimated full operating hours used during its useful machine life as follows:

$$Interest\ Cost = \frac{Total\ Interest\ Cost}{Gross\ Annual\ Operating\ Hours * Machine\ Usefull\ Life\ in\ Years * Operational\ Efficiency\ \%}$$

  Capital Financing Interest Rate: An annual interest rate stated as a percentage that is charged to borrowers of funds by banks and financial institutions. This financing rate is the basis for calculating the annual or hourly interest or financing expense as part of the machine hourly run rate. Capital Financing Interest Rate is country based.

- **Energy / Utility cost [€/h]:** It is the machine specific hourly utilities usage cost for electricity, compressed air, water and gas consumption as part of the part production process. These are the usages related directly to the operation of the machine and do not include any fixed cost types for overhead lighting, Plant HVAC, etc.

  This cost is not divided by the utilization rate as it is assumed that these costs are variable, i.e., are only incurred during actual operating hours.

$$Energy\ Utility\ Cost\ = Units\ of\ energy\ consumed\ per\ hour * Utility\ Energy\ Cost\ per\ hour$$

Energy / Utilities: Typically, resources consumed during the production such as compressed air for pneumatic actuators, water loss, natural gas, nitrogen, helium.

Machine utilities consumption generally are declared by constructor on machine technical data sheet.

The utilities unit cost depends on the manufactory country, for this reason a production process energy intensive could result more competitive on country where utilities has a lower unit cost.

- **Machine Maintenance cost [€/h]:** The cost per hour that represents maintenance, repair, and other variable expenses incurred during the normal machine value add production process.

  Calculation takes the annual machine maintenance expense and converts that to cost per hour shown below:

$$Machine\ Maintenance\ rate = \frac{Total\ Machine\ Maintenance\ Cost\ per\ Year}{Gross\ Annual\ Operating\ Hours * Operational\ Efficiency\ \%}$$

Annual maintenance cost includes expenses due to machine maintenance supplies, repair materials, etc. This allocation also includes the cost for maintenance labor, fringe and other costs related to the maintenance of the direct production machine and includes any special cleaning and handling that is above the norm.

- **Floor Space cost [€/h]:** it is the factory floor space overhead expenses, associated with the size of the specific machine and equipment production area. The current machine footprint size, supporting manufacturing areas, and production location are considerations when determining the floor space charge.

$$Floor\ Space\ Cost\ Rate = \frac{Total\ Machine\ Footprint\ * Floor\ Space\ Factor}{Gross\ Annual\ Operating\ Hours * Operational\ Efficiency\ \%}$$

- **Perishable Tooling / Supplies cost [€/h]:** The cost per hour for non-capital expense tooling, forming, machine supply items consumed in the direct production of the manufactured component and for other plant costs. The cost per hour is calculated below:

$$Perishable\ Tooling\ \&\ Supplies\ Cost\ Rate = \frac{Total\ Perishable\ Tooling\ \&\ Supplies\ Costs\ per\ Year}{Gross\ Annual\ Operating\ Hours * Operational\ Efficiency\ \%}$$

Perishable and supplies are non-capital expense items consumed such as sundry tooling, lubricants, forming materials, gloves, oils, and cutters stated and other industrial costs.

- **Insurance cost [€/h]:** The cost per hour of liability and casualty insurance expense related to the physical assets employed in the value-add part production process.

The cost per hour is calculated below:

$$Insurance\ Cost = \frac{Insurance\ Cost\ Factor\ \%\ * Total\ Machine\ and\ Installation\ Cost}{Gross\ Annual\ Operating\ Hours * Machine\ Usefull\ Life\ in\ Years * Operational\ Efficiency\ \%}$$

- **Property Tax cost [€/h]:** it is the property taxes on the value of the specific assets utilized in the part production manufacturing process. The total cost of insurance is based the location's tax assessment factor and cost basis valuation of the machine and equipment.

The cost per hour calculation provides for an estimated millage rate shown below:

$$Property\ Cost = \frac{Property\ Tax\ Factor\ \%\ * Total\ Machine\ and\ Installation\ Cost}{Gross\ Annual\ Operating\ Hours * Operational\ Efficiency\ \%}$$

So finally, we can calculate the machine cost by summing all the terms above:

Machine cost per hour

$$= \ Capitalization\ Cost + Interest\ Cost + Energy\ \&\ Utility\ Cost + Other\ Cost + Machine\ Maintance\ Cost + Floor\ Space\ Cost + Perishable\ Tooling\ \&\ Supplies\ Cost + Insurance\ Cost + Property\ Tax\ Cost$$

3.5.1.3 Mark-up

The mark includes three parts: Scrap, SG&A and Profit.

- **Scraps** are when product (or services) deviate from quality requirements or specifications.

  Producing defects represent a cost for the company because resource and time has been absorbed to produce a non-complain products.

  Cost of scrap and rework due to defects should be charged on good parts produced in order to recovered cost of resource spent.

  Usually scrap and rework costs for a process are charged as a percentage on value added by the transformation.

- **SG&A:** it is the acronym for Selling, General and Administrative Expenses. It is a major non-production cost presented in an income statement. SG&A expenses consist of the combined costs of operating the company, which breaks down to:

  <u>Selling:</u> The sum of all direct and indirect selling expenses, which includes salaries, advertising expenses, rent, and all expenses related to selling product

  <u>General:</u> General operating expenses, depreciation and taxes that are directly related to the general operation of the company.

  <u>Administration:</u> Executive salaries and general support and all associated taxes related to the overall administration of the company.

  We can represent the SG&A as percentage:

Figure 27 SG&A cost

- **Profit** instead is the final margin for the company operations. It should be calculated as below:

$$Profit = Price - Production\ cost - scrap\ cost - SG\&A\ cost$$

3.6.2 Diagram of the financial model

Depending on the analysis above, we can build a financial model of the production system shown in the diagram below:

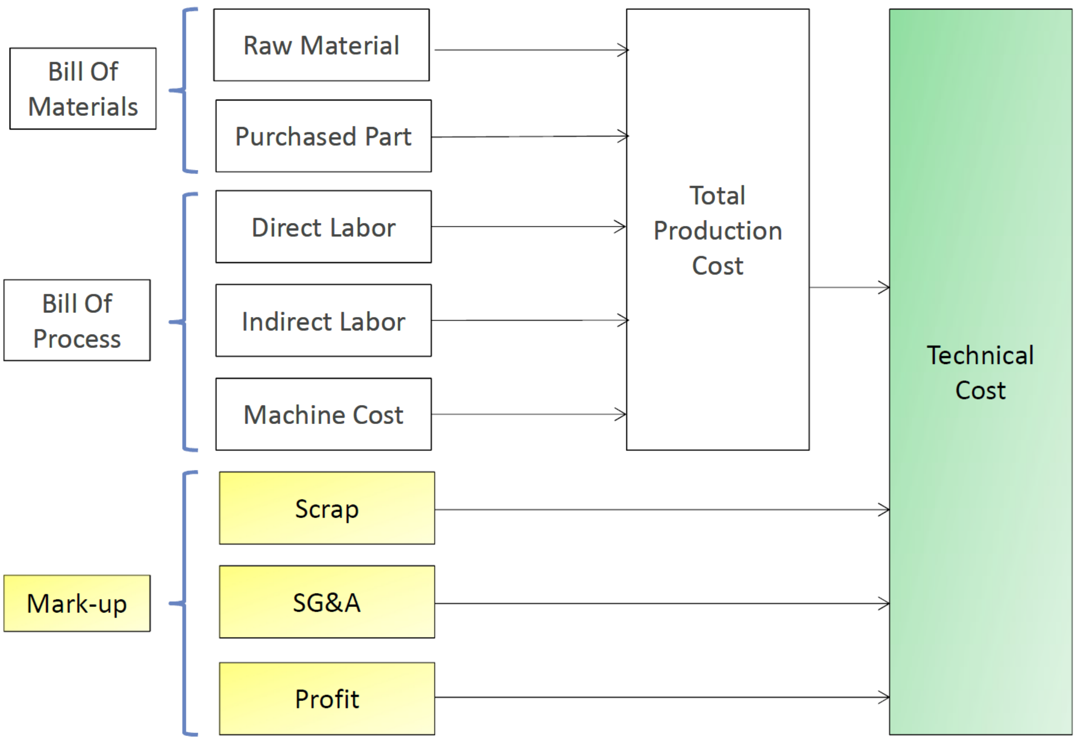

Figure 28 Financial model

3.7 The social model

The social model of the production system represents the environmental and social effects of the production system, these can be evaluated in several aspects.

- **Water:** we use water during the manufacturing process for many reasons, including cleaning, cooling, dilution and sanitation. Instead of releasing wastewater to sewers and storm sewers, factories can investigate ways of recycling water inside their plants. Water companies and water resources consultants can perform water audits to offer more detailed advice.

- **Air**: the production system may produce dust or toxic gas or greenhouse gas which can damage the environment. So, the production system should have a filtering system to avoid producing air pollution.

- **Energy:** The energy consumption is a critical problem the company should focus on. Reduce energy consumption is not only a profit for the company but also fulfill the principle sustainable development, which indicate the company's social responsibility.

  It is advisable to perform the energy audit. Energy audits are the process of evaluating which equipment or procedures are using the highest levels of energy. This information is valuable, as it pinpoints the specific areas that can offer the most improvement. Once a factory locates the worst offenders, they have a starting point for making reductions in their energy consumption.

  Energy audits can also lead to yearly savings on energy bills. The cost savings generated by energy-saving practices usually offset the investments companies make in implementing them. Small-scale changes can include using more efficient light bulbs, changing to lights with sensors and updating or adding insulation. Overall, less energy usage can translate to a smaller carbon footprint.

- **Equipment:** Aging equipment can waste energy by operating inefficiently. If repairs or part replacements don't lead to improvements, factories can replace outdated equipment with newer, more energy- and time-efficient models. Not only will newer models reduce energy consumption, but time savings may also decrease product turnaround times or eliminate bottlenecks. An energy audit will pinpoint the equipment and processes in need of the most improvement.

  Equipment releases a significant amount of waste heat energy. To take advantage of this wasted heat, factories can invest in cogeneration systems, which use the thermal energy produced by equipment to moderately heat water or heat spaces.

- **Recycle:** For the scraps generated by the production system, the company should try to reuse instead of discarding. Evaluate the scraps to find if there are any ways to recycle in the production system.

  The portion of using recycled source is also important to the company's eco-friendly strategy, so the company should to fully use the recyclable source from the waste.

- **Renewable energy:** The application of renewable energy like wind, solar and geothermal is also a way of reducing carbon footprint for a company. Using the renewable energy represents an advanced manufacturing style.

  Consider installing solar panels or coordinating with new wind farm construction. Many governments offer tax credits and subsidies to offset the cost of renewable energy.

- **Externality:** it refers to that the behavior of a person or an organization that make an effect to the other object (positive or negative), without gaining any benefit or being in commitments. For a production process, the manufacturer and the customer are the first and second party, and when the deal is done, it means that this deal is beneficial for both two parties, but when this deal has an effect on the third party, which is usually the society, this effect is the externality of this deal, as well as of the production process.

When it comes to the negative, it means that it has some bad effects on society like environment pollution; while if it is positive, it will be beneficial to the society even the company may not get any economic profit from this at once but in a long term, it will be helpful to improve the image and cultural of the company.

By check a production system according to the terms above, we can evaluate that how eco-friendly and society-responsible a production system is.

Chapter 4 Application to the practical case

Above all, we have already introduced a practical production case that the production of the corncobs powder and the production system hierarchical model, now we move to apply the hierarchical model to the practical corncobs production system by introducing a scheme flow. Then we will use the filtering system as an example.

4.1 General scheme

First, we develop a general scheme to describe a function of a layer among the hierarchical model of one device. This scheme is presented as a table:

Title
Description
Input
I/O transformation
Output

As can be seen from the table:

- **Title** is the name of the layer;
- **Description** is the description of the function of this layer for this device;
- **Input** is the input information from the upper level scheme or external source, which is necessary for describing the function of this scheme;
- **I/O transformation** is the steps needed to obtain the output from given input information
- **Output** is the output information from this scheme, which is of course the input of the next scheme.

4.2 The scheme flow of the Filtering system

In our application of the hierarchical model, we apply this model to each devices of the production system. Here we describe the application for the Filtering system as an example.

4.2.1 2D model layer

2D model
The plane layout of the Filtering system
Dimensions; **relative position**
Develop 2D AutoCAD drawing: we can obtain this information directly from the company or in some cases a direct inspection could be necessary
The plane layout

This is the first level scheme, the input information is from external source (Given data), and this is the fundamental layer of the device among a production system.

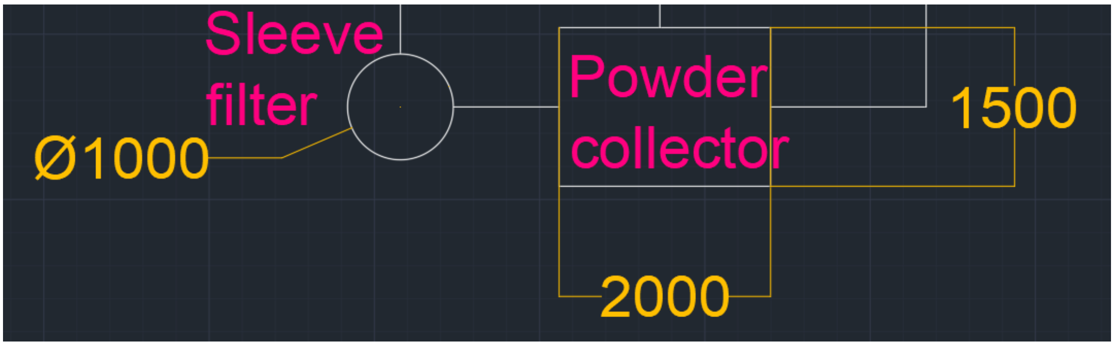

Figure 29 2D model of filtering system

4.2.2 3D model layer

3D model
the space occupancy of the Filtering system
plane layout; height of the device
Develop the 3D model by crossing information from the last scheme applying the height of the device with the AutoCAD
the exact position, space occupancy and operator interfaces

With the information of the plane layout from the upper level and the given height of the device, we can build the scheme of this layer for the Filtering system.

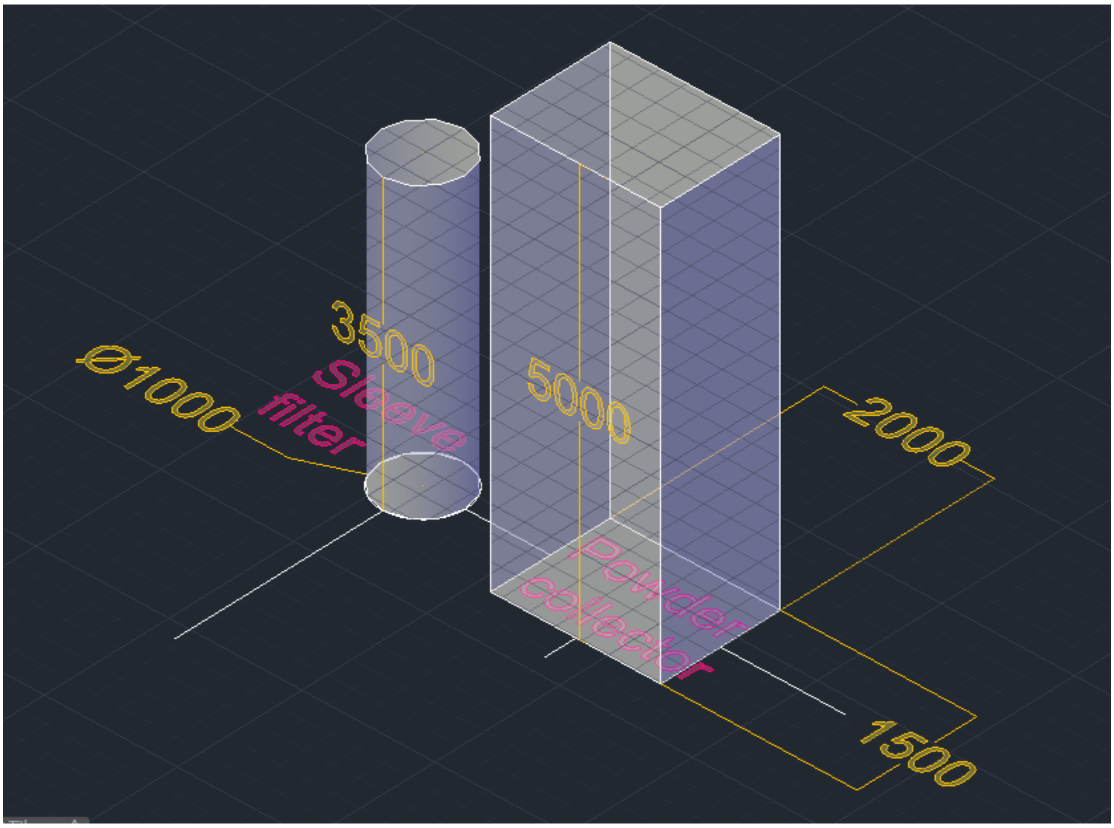

Figure 30 3D model of filtering system

4.2.3 The flow model layer

Flow model
Material flow of the filtering system
Layout; **amount of fine powder with dust;** **amount of fine powder without dust** **amount of output filtered powder;** **supplied electricity & compressed air**
Material flow analysis and comparison between the set data and measured data
Production efficiency; **Energy consumed**

At this layer, we input kinds of material flow related to the working of the filtering system which can identified according to the location of the device among the production system and with the total material flow chart of the production system. This material flows converge in the filtering system, indicating the material transformation within this device-filtering system. Thanks to the advanced sensors, all this information can be measured and collected automatically. We use sensors to detect the amount of fine powder with dust, fine powder without dust and output filtered powder, then this information will be translated to the processor to calculate the efficiency of the filtering system. And the electricity meter will tell us the energy consumption.

By analyzing all the information that comes into this layer, we can figure out the production efficiency and energy consumed of this device, which is necessary for the identification of several variables and KPI for the next level of layer.

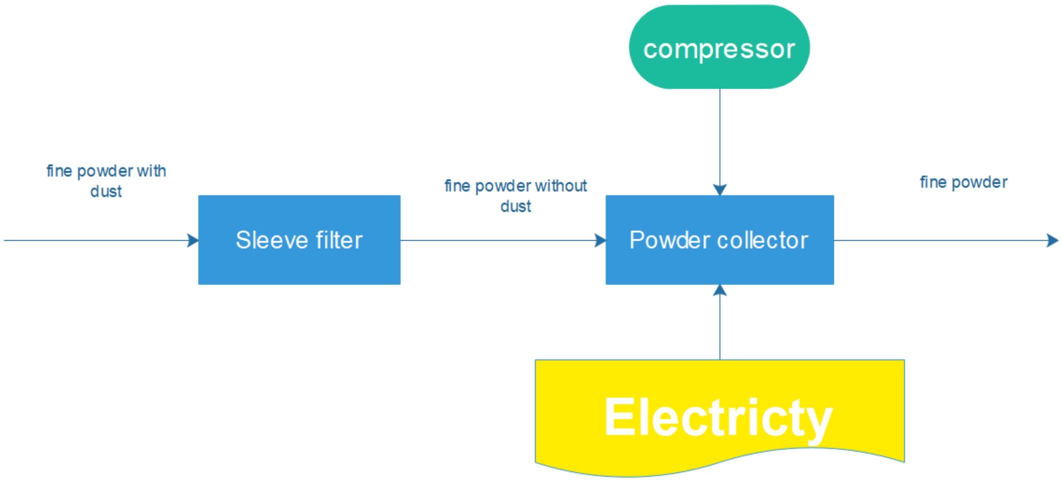

Figure 31 Flow model of filtering system

4.2.4 The variables model layer

Variables model layer
Regarding the kinds of variables and KPIs
Production efficiency; **Data from sensors:** **AUST, AUPT, AUBT, ADET, AOET, PBT, APT, AOET, PRI, PQ, RQ, GQ, EPC, CM, e, PL, STL, OL, TTF, TTR, FE, CMT, PMT, PDEI, ADEC**
Processor which contains the KPI formulas
KPIs: OEE, TE, MCI, CMCI, PCI, CPCI, CEC, FGR, PLR, STLR, OLR, ELR, CMR, DECE, DNECE, DEE, DNEE, A, AE, UE, SeR, AR, PR, TR, RR, QBR, MTBF=MTTF + MTTR

Within this layer, we use the technology of sensors to measure the information we need to acquire the value of different variables, and with the information of production efficiency from the last scheme, we can calculate the relative KPIs.

To realize this function, we can deliver all the information to the processor and can check these variables and KPIs of the Filtering system in real-time. By the process, we can evaluate the performance of the filtering system and analyze its effect on the whole production system.

4.2.5 The management model layer

Management model
Describe the production scheduling process
The KPIs; **production order;** **inventory level**
Collect and analyze the information by using ERP
Production scheduling adjustment

With the KPIs from the last scheme and according to the production order inventory level, we can modify the production schedule and provide a production scheduling adjustment solution.

In our case, we can modify the production schedule of the filtering system according to the available information, which is affected by the whole production system.

4.2.6 The financial model layer

Financial model
The financial cost of the good produced
Net Annual Operating Hours, Capitalization cost, Interest cost, Energy / Utility cost, Machine Maintenance cost, Perishable Tooling / Supplies cost, Insurance cost, Property Tax cost; Indirect Labor cost Energy consumption; Raw material cost
Cost Calculation formulas
Good production cost

According to the Energy consumption from pervious and all the cost data above, we can calculate the good production cost, which is the hourly cost of the filtering system.

Let's assume that:

Net Annual Operating Hours=270*7=1890 h;

Capitalization cost=3000 €/year;

Interest cost=0 (we buy them in cash);

Energy consumption=17kw

Energy cost=17 kw*1890 h*0.21 €/kwh=6747 €/year;

Machine maintenance cost=3*12*200 €=7200 €/year (3 times per month, 200 € for each);

Perishable Tooling / Supplies cost is included in maintenance cost since the tool of filtering system is the filter element;

Indirect Labor cost=23 €/h (which is the gross salary that the employer needs to pay)

Raw material cost=100 €/t;

Production rate=5 t/h

Finally, the good production cost is:

[(3000+6747+7200)/1890+23]/5+100=106 €/t

4.2.7 The social model layer

Social model
The social effect of the device
Energy consumption; Contaminant emission; Externality of the production
Social effect calculation formulas
Social effect index

This scheme is to evaluate the social effect of the filtering system, we gather the required information from the previous schemes and out resource, then with a social effect evaluation formula, converts these inputs into the social effect index of the filtering system.

Besides that, in an intuitive way, the social effect can be evaluated as the externality of the production. In our case, first, the corncobs are purchased by the company otherwise they can be a kind of agricultural waste, so it is a positive effect towards the society to avoid the waste of source and recycle it.

Regarding the purpose of corncobs powder, it can be positive or negative. For example, as a biofuel, it saves the consumption of other regular resource while it can produce too much dust during combustion which can be negative for the environment; As a cleaner for the building surface, it can be very healthy for workers since it is non-chemical cleaner, but it can not evaporate by itself and be a kind of rubbish; As the cat litter, which is cheaper than others like silica litter, but it can be eaten by mistake by cat and have some effect on health of the cat.

In a word, the production of the corncobs has more positive effect so we can say that it has a positive externality for the society.

Bibliography

- Kagermann, H., W. Wahlster and J. Helbig, eds. **Recommendations for implementing the strategic initiative Industries 4.0: Final report of the Industries 4.0 Working Group.** 2013
- Lee, C.M, Chan, Y.L., Gan, Y.L., Tang, T.K., Tan C.P. and, Lai, O.M. **Physicochemical and sensory analysis of instant cereal beverage incorporated with corncob powder,** Food Research. 2018, 2(5): 453 – 459;
- Lydon, Bill. **Industry 4.0: Intelligent and flexible production.** InTech Magazine 2016;
- P. Suwignjo, U.S. Bitici, A.S. Carrie. **Quantitative models for performance measurement system**. International Journal of Production Economics. 2000, 64(1): 231-241;
- Bongsug (Kevin) Chae. **Developing key performance indicators for supply chain: an industry perspective**. Supply Chain Management: An International Journal. 2009, 14(6): 422-428;
- Aref A. Hervani and Marilyn M. Helms. **Performance measurement for green supply chain management**. Benchmarking: An International Journal. 2005, 12(4): 330-353;
- Peter Muchiri, Liliane Pintelon, Ludo Gelders, Harry Martin. **Development of maintenance function performance measurement framework and indicators.** International Journal of Production Economics. 2011, 131(1): 295-302.
- ISO 22400-1, **Automation system and integration-Key performance indicators (KPIs) for manufacturing operations management-Part 1: Overview, concepts and terminology,** 2013;
- ISO 22400-2, **Automation system and integration-Key performance indicators (KPIs) for manufacturing operations management-Part 2: Definitions and description,** 2014;
- Wolfgang Kuehn. **Digital factory – simulation enhancing the product and**

production engineering process[C]. Proceedings of the 2006(38th) Winter Simulation Conference: 1898-1906;

- Hasse Nylund, Kai Salminen, Paul Andersson. **Digital virtual holons – an approach to digital manufacturing system [J].** Manufacturing Systems and Technologies for the New Frontier, 2009, Part 3, 103 – 106;
- J E Muelaner, P G Maropoulos. **Integrated dimensional variation management in the digital factorys**, [C]. Proceedings of DET 2011, 7th International Conference on Digital Enterprise Technology, Athens, Greece, 2011: 39-46;
- Wolfgang Kuehn. **Digital Factory – Integration of simulation enhancing the product and production process towards operative control and optimizations[J].** International Journal of Simulation, 2008, 7(7): 27-39;
- Ningxuan Kang, Cong Zhao, Jingshan Li & John A. **Horst A Hierarchical structure of key performance indicators for operation management and continuous improvement in production systems**, International Journal of Production Research, 2016, 54:21, 6333-6350;
- Takaya Ichimura. **The elements and functions of hierarchical scheduling system of order production.** International Journal of Production Economics 44 (1996) 73-81;
- Hiroshi Katayama. **On a two-stage hierarchical production planning system for process industries.** International Journal of Production Economics 44 (1996) 63-72;
- Wikipedia: Corncob: https://en.wikipedia.org/wiki/Corncob
- Wikipedia: Material Flow Analysis: https://en.wikipedia.org/wiki/Material_flow_analysis
- Greentumble: Environmental Impacts of Factories and How They Can Improve: https://greentumble.com/environmental-impacts-of-factories-and-how-they-can-improve/