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Application of fuzzy methodology for KPIs implementation in manufacturing execution system

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Abstract

Performance evaluation is an essential part that contributes to the development and success of an enterprise, because it helps decision-makers to concentrate more on the most critical operations and elements considering the 20/80 rule. The performance evaluation can be operated at different levels corresponding to the hierarchical structure of enterprises. This thesis establishes a five-dimensional model using fuzzy mathematics and analytic hierarchal process to carry out performance evaluation at the intermediate level of an enterprise, manufacturing execution system (MES). The five dimensions are significance, frequency, predictability, observability and time sensitivity; each of them characterizes the critical operations and elements, while the operations and elements are measured by key performance indicators (KPIs) both from ISO 22400 and newly-defined. Weights of each KPIs are calculated using the five-dimensional model with Excel and MATLAB, then actions can be taken to rearrange the concentration and achieve the improvement of value-added process.

Keywords: key performance indicator (KPI); fuzzy mathematics; ISO 22400; hierarchical process; weighting

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List of Acronyms

ACT	Actual cycle time
AEC	Actual energy consumption
AHP	Analytic hierarchy process
AOET	Actual order execution time
APAT	Actual personnel attendance time
APWT	Actual personnel work time
AUBT	Actual unit busy time
BSC	Balanced scorecard
CEP	Complex event progressing
CI	Consistency index
CR	Consistency ratio
EBT	Effective busy time
ERP	Enterprise resource planning
FAHP	Fuzzy analytic hierarchy process
IC	Inventory cost
KPI	Key performance indicator
MES	Manufacturing execution system
MOM	Manufacturing operation system
OKR	Objective and key results
PBT	Planned busy time
PCS	Process control system
PCT	Planned cycle time
PEC	Planned energy consumption
RI	Random index
RM	Raw material
S, F, P, O, T	Significance, frequency, predictability, observability, time sensitivity
SOP	Standard operating procedure
TFN	Triangular fuzzy number
VDMA	Mechanical engineering industry association

1. Introduction

Along with the economic development and social progress, information technology has become more and more important in all respects, including manufacturing, agriculture, business and so on. Information technology represents the development direction of nowadays advanced productivity forces, whose widespread use enables the important production factors and strategic resources to do their work. Thus, the resource allocation can be achieved more efficiently, promoting the continuous upgrading of labor productivity in traditional industries as well as social operational efficiency.

As far as industrial enterprises are concerned, information technology promotes enterprises' upgrading in the following aspects. First, the embedding of information technology into traditional mechanical and instrumentation products, that is to say, mechatronics, makes them intelligent and networking, which is the important direction of upgrading. Second, computer-aided design technology, along with network design technology, improve significantly the technological innovation capabilities of enterprises. Third, the realization of automatic control of the product manufacturing process achieved by usage of computer-aided manufacturing technology or industrial process control technology is able to improve significantly production efficiency, production quality and yield. Forth, overall optimization can be obtained through the application of information technology systems, by achieving scientific management of the enterprise as well as unified integration of the allocation in terms of human resource and so on. Last but not least, the application of Internet to conduct e-commerce, supply chain and customer relationship management can promote the upgrading of business ideas and business methods, which can improve the enterprise's competitiveness and obtain economic benefits. What's more, information technology represented by the Internet is also a powerful tool to promote the modernization of agriculture and the tertiary industry.

In summary, the ubiquitous information, or data, will guide the way to a smart world. It's vitally necessary for enterprises to follow this trend.

1.1. Industry 4.0 and enterprise information integration

The fourth industrial revolution (as shown in Figure 1.1), or industry 4.0, was revived in 2011 at the Hannover Fair [3] and represents the combination of cyber-physical systems, the Internet of things, and the Internet of systems[10], has been bring the leading-edge solutions into spotlight.

The concept industry 4.0 includes a transformation from centralized control mode to enhanced distributed control mode, connecting things and services through the entire enterprise by network. The distributed control means the ability of cyber physical systems to make decisions on their own and to perform their tasks as autonomously as possible[17]. In other words, the factory is "smart". It's not only a change in value-added process, but also changes in manufacturing thinking and innovation. The intelligence can be implemented in 4 aspect, as shown in Figure 1.2., production, energy management, equipment and supply chain, jointly promoting the realization of industry 4.0.

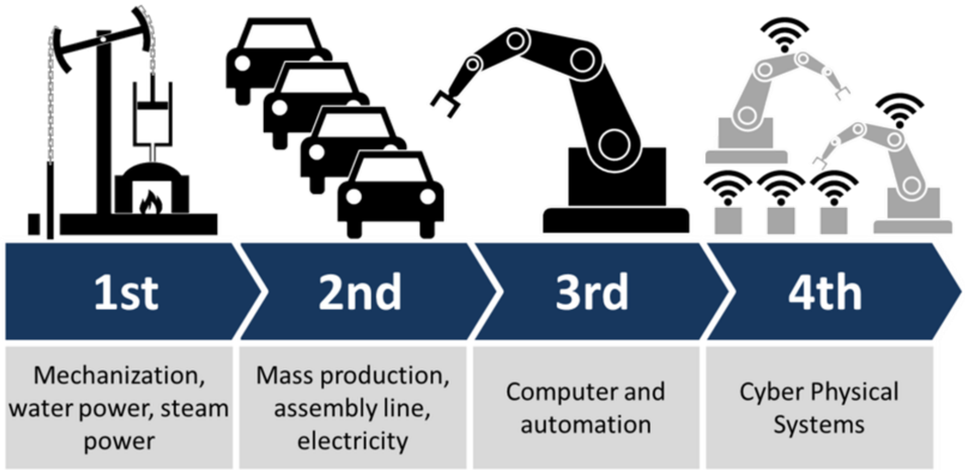

Figure 1.1 The 4 Industrial Revolutions (by Christoph Roser at AllAboutLean.com)

Intelligent production includes intelligent process control, intelligent logistic management, intelligent man-machine interaction system and so on, which finally contribute to the improvement of value-added process by increase efficiency and lower the cost. The essence of constructing a smart plant is based on so-called "CPS", computing, control and communication.

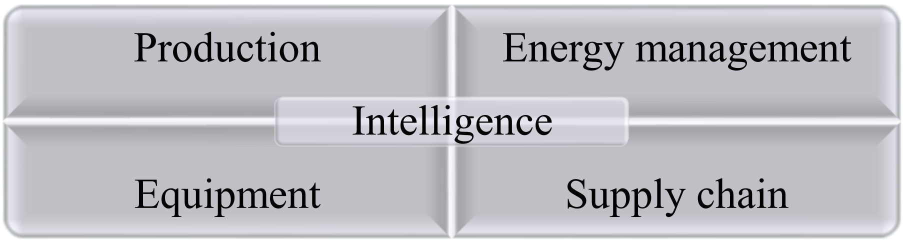

Figure 1.2 Intelligentialize of plant through industry 4.0

As the fourth revolution progresses, in the future, machine is no longer driven by oil or electricity but by data. The focuses of companies will shift from enterprise scale, standardization and power to flexibility, agility, personalization and user friendliness. What's more, the market environment, developing mode and processing efficiency for manufacturing companies have changed a lot. The simplex, isolated improvement of a limited local aspects is far more from enough. Enterprises must go in the direction of integration and synthesize to enhance the core competitiveness on the basis of computer and network science, that is to say, the information integration.

For decision-making management of enterprise, there are many systems with the application of information technology, like material requirements planning, enterprise resource planning, just in time and agile manufacturing. Enterprise resource planning is not only a software, but a decision-making system on the basis of information technology, which takes the financial as its core and integrates production, supply, sale, people, finance and logistics. It is able to do historical analysis and future prediction, but not so real-time. As to the actual production process, process control systems matters the specific operations as the fundamental parts of enterprises. The application of programmable logic controller and distributed control system contribute to the high degree of automation and increase of quality as well as quantity.

However, there is a wide gap between top and bottom levels for the information integration. There are two main reasons.

1) The differences in time frame; time frame at enterprise top level is general days, months or even years while time frame at bottom level is generally hours, minutes, seconds or even real-time. This difference results in difficulties in communicating and scheduling;
2) The different focuses of two levels; the top level always focuses on a long-term goal, for example, annual income and market share, while the bottom level focuses on the current work, such as daily production quantity. It's really difficult for the top level to monitor and control the specific operations at bottom level, which means that the target might not be achieved.

In order to solve these problems, a three-level enterprise structure was proposed by American Advanced Manufacturing Research (AMR) in 1992, as shown in Figure 1.3.

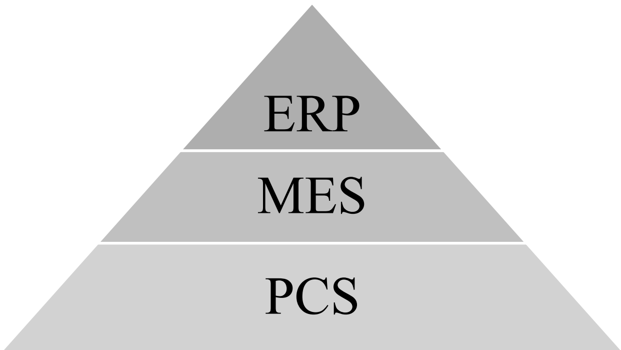

Figure 1.3 Structure of an enterprise proposed by AMR, 1992

The top level, enterprise resource planning (ERP), focus on flexibility and real-time performance of enterprise management, so as to reduce inventory cost and increase value created in the context that customer satisfaction and market requirements are met. The intermediate level, manufacturing execution system (MES) emphasizes the control and execution of plan, integrates dynamically the production field with upper management layer by decomposing and refining the plan. The bottom level, process control system (PCS), focuses on the actual control of production process, should be able to guarantee a stable and ordered production by means of various advanced device and technics like programmable logic controller and distributed control system.

MES is an important part for an enterprise, which connects the top and bottom level, and behaves as a bond to solve the difficulties in communication. On one hand, MES decomposes and refining the plan from EPR level to practical instructions, assigning them to PCS level; on the other hand, MES monitors in real time the running status of PCS, collects data and gives feedback to ERP level after data analyzing and processing.

1.2. Performance evaluation of an enterprise

For an enterprise, the human resource management level determines its developing speed as well as competitiveness to a certain extent. Only by doing a good job in human resource management can the core competitiveness of an enterprise be enhanced so as its core competitive advantages. Therefore, one of the urgent problems for enterprises at the present stage is to constantly improve the employee management level of enterprise. Management scientists believe that the important thing to improve the level of enterprise management is the objectivity and accuracy of evaluation.

Performance means good ranking with the hypothesized conception of requirements of a role[18]. The success of an enterprise needs each of its department and employee pulling in the same direction, which can be enhanced by some stimulate measures. By completing the targets of individuals, the goal of enterprise can be achieved. That's what performance evaluation does. The behaviour and outputs are measured quantitively or qualitatively to verify if the targets are met or not, then some actions like correction or awards are performed, also feedback is given for further improvement. For the vast majority of managers especially those in human resources, performance evaluation management is both an emphasis and a difficult in the process of management, which, however, plays a vital role in the development of enterprises. The achievement of enterprises' strategic objectives is impossible if the performance evaluation systems works badly. Under normal circumstances, the enterprise and its members can evaluate as well as recognize the achievement of work objectives through performance appraisal results, based on which the promotions, transfers, rewards and punishments of employees can be determined. Practice has proved that based on the results of performance appraisal, problems and deficiencies existing in the management can be found out and then be corrected. Through improvement and refinement, the enterprise can achieve long-term sustainable development

According to the structure of an enterprise as shown in Figure 1.3,performance evaluation can be executed at three levels, ERP, MES and PCS, and at each level, performance is measured for individuals, missions and departments. This thesis focuses on the performance evaluation of MES.

1.3. Structure of thesis

This thesis establishes a five-dimensional key performance indicators model to adjust the focuses on operations and elements at MES level, so as to improve the value-added process.

In chapter 1, industry 4.0 and information integration in an enterprise are briefly introduced;

In chapter 2, enterprise structure and performance evaluation methods of MES are discussed;

In chapter 3 (important part), KPIs based on *ISO 22400 Automation systems and integration. Key performance indicators (KPIs) for manufacturing operations management*[5] are introduced, then the selection criteria of KPIs for an automotive discrete plant is discussed, using complex event progressing; also, the KPIs calculation is specified;

In chapter 4 (important part), a five-dimensional model is established to determine the weight of each selected KPI and the implementation method is developed applying fuzzy mathematics and MATLAB program;

In chapter 5, the model is implemented and analyzed in a specific case with Excel and MATLAB;

In chapter 6, a conclusion that the adjustment of focuses on plant operations and elements is able to improve the value-added process is drawn.

2. Manufacturing execution system

Performance evaluation of an enterprise may be various considering the industry categories, enterprise scale and also enterprise structure. In this thesis, attention is paid at the intermediate level of enterprises, manufacturing execution system or manufacturing operating management.

2.1. Manufacturing enterprise

Manufacturing is the process of converting raw materials, components, or parts into qualified products, and can be classified by different criteria, for example, the typical classification by production means can be demonstrated as make to order, engineer to order or project, make to stock, continuous manufacturing, batch manufacturing and discrete manufacturing.

The functionality hierarchy of an enterprise is defined by international electronical commission (IEC) and is shown in Figure 2.1. Corresponds to the classification of production, the control at fundamental levels is also classified as three types: batch control, continuous control and discrete control. An enterprise is divided into 4 levels; the level 0 to 3 is related to process control system, that is to say, sensing, monitoring and supervising the actual production process; the level 2, manufacturing operations managements (MOM), which also referred to as manufacturing execution systems (MES), describes the intermediate layer of enterprise; the level 4, business planning and logistics, corresponds to ERP level in AMR mode defined in Figure 1.3, specifying the basic enterprise targets and managements.

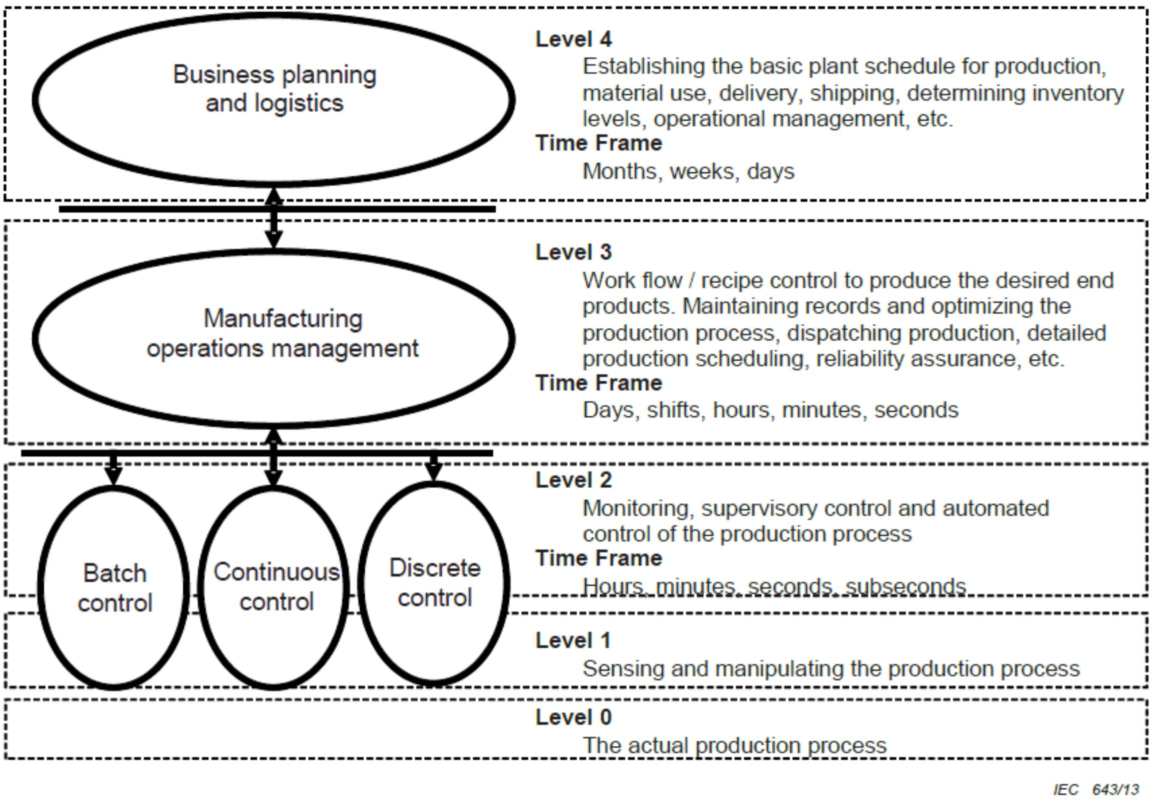

Figure 2.1 Functional hierarchy adapted from IEC 62264-1[4]

Discrete manufacturing has several features; the final product of discrete manufacturing must be composed of limited and countable parts and can be expressed by tree topology with explicit relationships, what's more, the parts might be manufactured at the same period and are assembled according to this topology. For example, the production of automotive and computers. The entity of discrete manufacturing is typically solid, including raw material and products. For small-quantity and multi-varieties manufacturing, the arrange of plant is determined by processes in stead of products, so it's necessary to dispatching material in production.

Batch manufacturing, unlike pure discrete manufacturing, on one hand, doesn't have a fixed recipe of ingredients or bill of resources, on the other hand, has a clear execution sequence to determine which operation should be performed next. What's more, there are many types of products according to requirements, for example, medicine and drinks, which means their raw material might have large difference, and the plant must have the ability to process different material.

Continuous manufacturing generally has only simplex product, whose process cannot be interrupted with fixed processing sequence. Continuous manufacturing has a higher efficiency and lower waste compared to discrete and batch manufacturing. The products of continuous manufacturing are often the raw material for other plants, such as petroleum and steel.

The physical equipment can also be discussed with a hierarchical structure defined by IEC as shown in Figure 2.2.

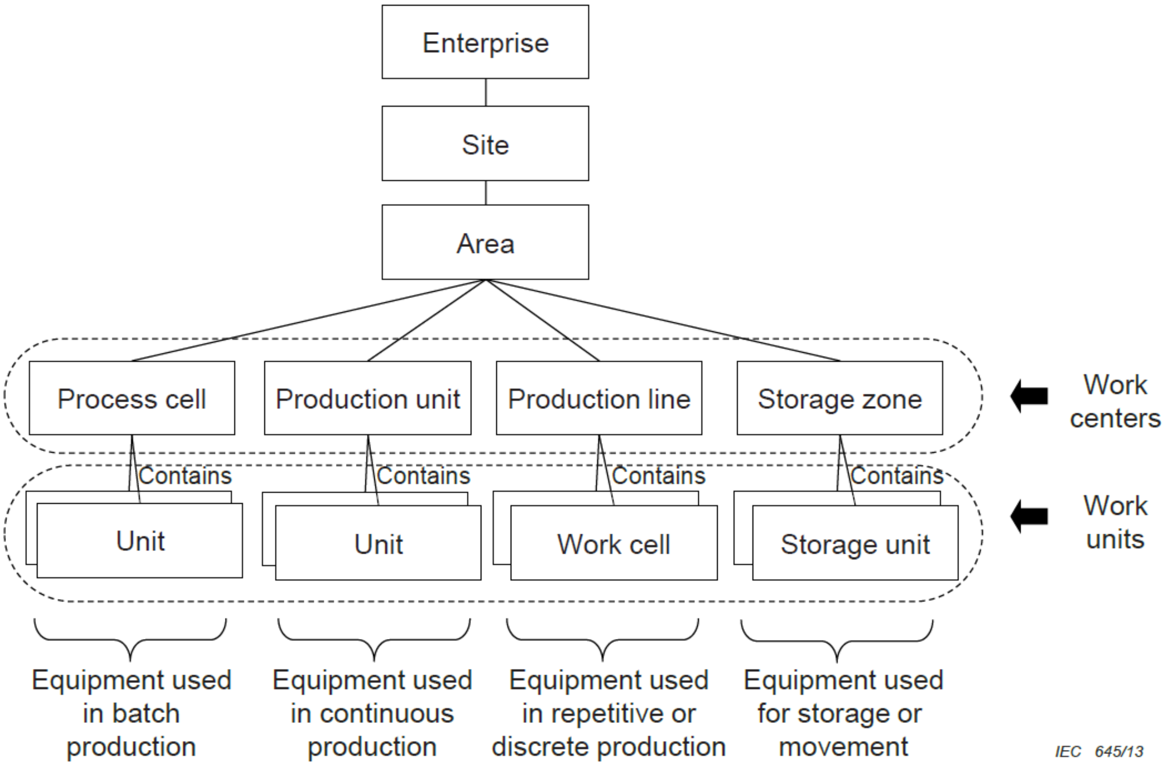

Figure 2.2 Role based equipment hierarchy adapted from IEC 62264-1[4]

According to the role-based equipment hierarchy, equipment used in batch production at work center level is process cell containing work unit; while equipment used in continuous production is production unit containing work unit, and equipment used in discrete production is production line containing work cell.

2.2. MES and its performance management

Manufacturing execution system (MES) is an information system as well as the critical part that forming a connecting link between the preceding and following in enterprise hierarchical structure. It collects all the data information and status information from order accepted to goods finish, achieving optimal management of value-added process by interacting with upper planning level and lower production level. MES is able to react quickly when an incidence occurs in plant, giving suggestions or handling directly the incidence. This capability reduces lots of efforts which have nothing to do with the value-added process thus contributes to achieve the enterprise’s profit target.

With the rapid increase of informatization level in manufacturing field, manufacturing execution system is demanding a complete, modern performance management system to guarantee its sustainable development. With regard to performance, there are three main perspectives. One view is that performance is behavior, while another view is that performance is the result, and the third one is that performance is the combination of employee behavior and ability. The so-called performance management system refers to the continuous circulation process of managers as well as employees at all levels, in which participating in performance planning, performance coaching communication, performance appraisal evaluation, performance result application and performance goal improvement, in order to achieve goals of organization. The performance assess of employees is supposed to be integrated with enterprise business objectives, whose results are part of enterprise human resource management. In addition, the evaluation process in terms of working attitude, capability and achievement should be subjective and accurate, based on employees’ behaviours as well as performance. The internal performance of an enterprise can be divided into the following levels. First, the performance at organizational level, that is to say, the quality and efficiency of the organization's completion of the goal; secondly, the performance at the department and team level, which is the quality and efficiency of departments as well as teams to achieve the goal; thirdly, the performance at employee's personal level which is the basis of organizational performance and team performance. As we can see, the third level, that is to say, individual performance, is the core and fundamental of enterprise performance management.

The evaluation system should combine the staff and operations, achieving the functions of objective planning, performance evaluation and results feedback. The system provides upper levels with analysis and results deriving from resource availability, equipment capability, worker efficiency etc., to improve the decision-making at upper layer What’s more, the performance management should be generally online and have the ability to adapt itself to complex changeful market conditions. An eligible performance evaluation system is capable of achieving a win-win situation for both the enterprise and the employees.

There are various performance evaluation systems, such as balanced score card, objective and key results, key performance indicator; the former two methodology are briefly introduced in this section while the last one is explored detailly in the following chapters.

1) Balanced scorecard (BSC) performance evaluation system is a widely used performance management tool whose ideal is based on the close relationship between performance management and strategic objectives, regarding the achievement of financial goal as a vital part in enterprise development, but also taking into account sustainability as well as customer satisfactory. Therefore, in the execution of performance assessing, several factors should be included, which are optimization of financial activities and business processes, improvement of customer satisfaction as well as continuous learning ability.

   The advantages of BSC are detailed decomposition of abstract strategic goal and overall considerations in multiple dimensions avoiding focusing only on finance. However, BSC also has significant shortcomings; the system is redundant and does not pay enough attention to employees and suppliers.

2) Objective and key results (OKR), first launched by Intel, is able to separate objectives and performance. OKR has several key requirements. First, the goals should be clear, innovative and forward-looking but at the same time challenging which are set by the means of enterprise and its employees working together, so as to stimulate the initiative and vitality of employees. The key results should be quantifiable as much as possible, also parameters such as quantity, quality, and time should be specified. Last but not least, OKR should be open, fair and transparent. Only in this way can we strengthen the supervision and build the project team easily.

   Enterprises are able to gain benefit from OKR. When an enterprise introduces OKR, first the enterprise target is set, then the corresponding targets at project group level, management level and grassroots level are set step by step, forming a sound and perfect target system. By this way, the enterprise operates as a whole in an orderly manner according to the target, enabling employees to spend time on the goal of completing the project. With the OKR target management system, it is possible to organically link decision-making levels with employees at all levels, integrating goal and objectives of the enterprise, enabling cooperation to achieve final goal. There are also disadvantage that if the description of key results too simple and scarce, the results of the assessment will be too subjective and lacking authenticity, thus the significance of assessment is lost.

3) Key performance indicator is a techno-economic indicator for evaluating process and performance. From the Pareto efficiency, or the 20/80 rule, roughly 80 percentage of the results come from 20 percentage critical causes [8], which indicates that the effective way to improve value-added process is to focuses the 20 percentage key factors, i.e., the key performance indicator. This method is an operational and feasible enterprise performance evaluation index system formed by refining the strategic goals of the enterprise. When adopting this method, it is necessary to select operations or elements content that is closely related to the enterprise' objectives, then formulating the corresponding practical and feasible assessment content. The KPI method enables enterprise members to clarify performance indicators as a whole and thus quantify the indicators to improve their ability. The key part of this assessment method is to construct the assessment index system with feasibility and operability.

The main steps of clarifying KPIs are expressed as follows. First, the KPI at enterprise level based on its strategic goals should be defined. Then, the high-level KPI are decomposed effectively as well as systematically into departmental level, with the establish of department KPIs and improvement of KPI evaluation system. Then the department KPIs are again decomposed effectively into individual KPIs, the performance measurement indicators of each position are clarified, which are used as medium by employees to clarify the elements and reasons for the assessment. The next step is to set the evaluation criteria accurately, clarifying the correct requirements and direction of measurement. An additional step is to enhance the review of KPIs so that the comprehensiveness and accuracy are fully guaranteed.

The implementation of KPI has many advantages. Members at all levels can clearly define the content of the target, thus the enterprise and individual interests can be integrated effectively. In addition, KPI method enables the decision-makers concentrate on the activities which have the most contribution to value creating process and also enable them to react quickly to the potential problems; what's more, KPI help MES with self-perfecting by calculating, comparing values and taking corrective actions according to the feedback. However, the KPI performance appraisal method also has disadvantage. It's not easy to define effectively quantifiable KPIs at all levels. What's more, the evaluation is likely to fall into a mechanical assessment mode, the combination with income, that is to say, immediate benefit, may cause forgotten of long-term goals. So, numbers should not just mean simple numbers, in stead they should be the result of a combination of complex behaviors based on multiple perspectives, and should be treated carefully.

3. Key performance indicator for MES

The mechanical engineering industry association (VDMA) had first focus on KPIs in manufacturing field and put forward 22 typical KPIs for evaluating MES; additional KPIs are defined by international standard organization in *ISO 22400 Automation systems and integration – Key performance indicators for manufacturing operations management* [5]. The KPIs used in fuzzy analysis in this thesis are both based on *ISO 22400* and defined on specific requirements.

3.1. Key Performance indicator overview

KPI is defined as quantifiable and strategic measurements that reflect an enterprise's critical success factors [6]. It can be obtained by breaking down an enterprise's epic goal into multiple much smaller operable and feasible objectives, each of which has its own specific features. The procedures to select KPIs are as shown in Figure 3.1. Once the key elements or operations are selected taking into account the 20/80 rule, KPIs can be defined and described according to the international standard organization files.

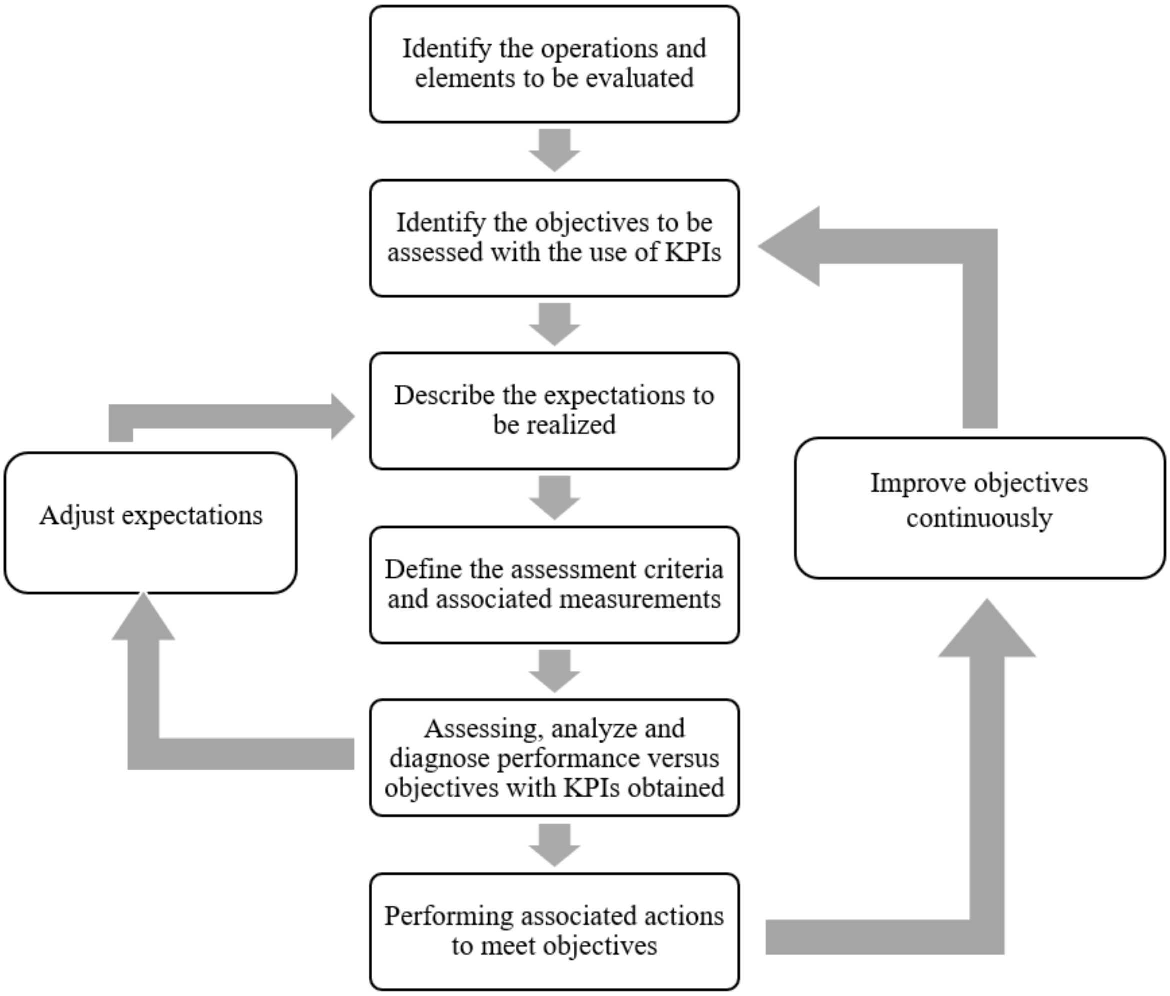

Figure 3.1 Procedures to define and select KPIs

The definition can be completed through several steps. KPIs are quantifiable or measurable, which means they can be expressed by numbers. This is an important aspect that should be taken into consideration during the selection; the measure of objectives should be practical and feasible. The expectations to be met are derived from decomposition of enterprise's target, then the measurements are obtained by technical methods. The values of KPIs are used to assess the performance and at the same time act as inputs for diagnose as well as further correction. This system is dynamic and if the expectations are changing with exterior reasons like market conditions, adjustment can be performed continuously.

The *ISO 22400* has defined a general structure to express KPI's specifications used for manufacturing execution system performance evaluation, which is divided into two parts: content and context [5], as shown in Table 3.1. In the content column, KPI name, description, formula and range are defined, which are the instructions for usage of KPIs; in the context column, timing and model diagram are specified, which are the necessary complementary aspects to be considered. Range defines the maximum and minimum possible value of the KPI, and trend indicate the right direction in which the adjustment should move in. What's more, timing is the frequency that measurements should be done for use of audience. Production methodologies are continuous, discrete and batch. The effect model diagram illustrates the logic of KPI.

Table 3.1 KPI description

KPI description	
Content	**Context**
Name	Timing
ID	Audience
Description	Production methodology
Scope	Effect model diagram
Formula	Notes
Unit of measure	
Range	
Trend	

3.2. KPIs selected for a typical manufacturing plant

KPIs selection are different when it comes to various industry. In this section, 14 KPIs either selected according to *ISO 22400* or defined on-demand are used to compose a performance evaluation system for a typical manufacturing plant.

3.2.1. Selection criteria

KPIs are in corresponding to various events in the plant. The selection of KPIs in a plant specifies which events should be concentrated more, in other words, which events are the most influencing ones to the value-added process. To achieve this selection in a manufacturing plant, some methodology or criteria are applied. Generally, critical success factor method, strategic objectives decomposition, key business area method or the combination of them are used.

For the first step, to identify operations and elements to be evaluated, critical success factors should be figured out. The operations and incidences in a plant can be seen as events. To identify the most important events, a methodology called complex event progressing is used. Complex event progressing can simplify the use of algorithms for finding and capturing trading opportunities[1]. Complex event has some properties as shown in Figure 3.2. When analyze a complex event, the following aspects should be considered. Disturbance and exception as the properties for an event means that the event can be affected by unplanned or uncontrollable changes. Uncertainty indicates that there is more than one possible result for a specified behaviour. Disturbance, exception and uncertainty may affect the key indicator values; thus, these properties or features can instruct the classification of complex events in a manufacturing plant.

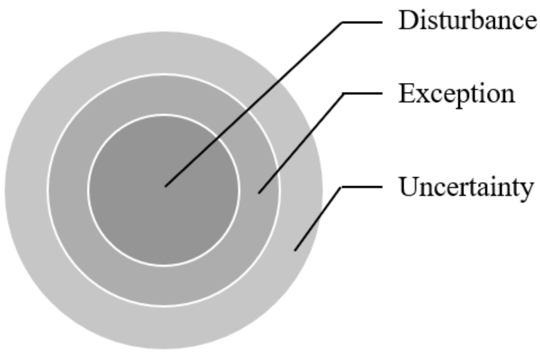

Figure 3.2 Complex event properties

This thinking helps to sort the complex events in a plant, so as the corresponding KPIs. Disturbance and exception can be sort by different aspects. When classified by its sources, disturbance and exception may come from exterior and interior. Exterior resources include upstream as well as downstream department or environment, for example order placing and refund, while interior resources come from the intrinsic properties of complex event, such as equipment operating status and raw material quality. When classified by property, disturbance and exception can be sort into quality-related ones, time-related ones and cost-related ones, or random and systematic ones. Uncertainty in manufacturing plant includes non-constant parameters such as processing time, delivering time and tool missing, whose sources can also be sort into interior and exterior. To conclude, the complex events in plant can be sort into two types according to their sources, intrinsic events and exterior events. Then the four steps to select KPIs as shown in Figure 3.3 are performed.

Further than that, intrinsic events are sort into cost-related events, quality-related events and delivery-related events, while exterior ones are sort into upstream and downstream events. Next the critical operations and elements in each classification are found out, followed by the defining of critical success factors. Finally, the KPIs are determined.

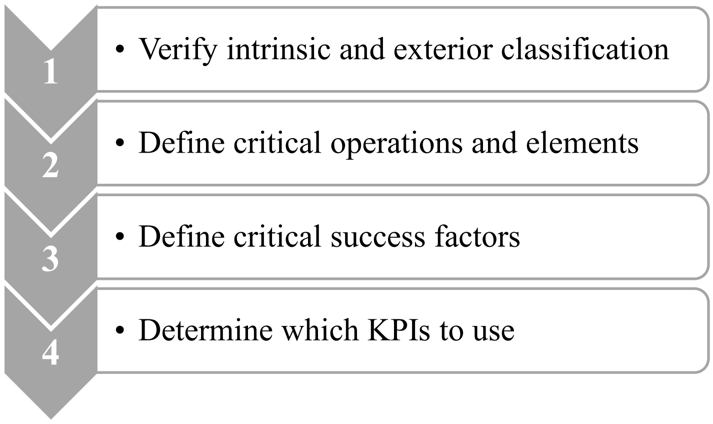

Figure 3.3 KPIs selection according to complex event progressing

3.2.2. Selection results

Events in plant are analyzed hierarchically. The causes arising disturbances, exceptions and uncertainties are classified to two types, as stated in the last paragraph, exterior and intrinsic. For exterior type, the causes come from both upstream and downstream departments that have influence on the value-added process, for interior type, the sources come from cost-related, quality-related and delivery-related operations and elements, as shown in Table 3.2. For upstream and downstream sources, the disturbance, exception or uncertainty come are mainly related to the coordination and flow of material, cash and so on. The sudden change in surroundings cause change in the events. For intrinsic sources, the influences are much more direct, therefore are more important. The entities inside a plant are concerned, such as staff, equipment and power.

Table 3.2 Critical operations specification in a manufacturing plant

Types	**Sources**	**Possible affecting events**
Exterior events	Upstream department	Bad coordination
		Unqualified raw material
		Rush orders
	Downstream department	Bad coordination
		Sudden change of delivery time
		Return or refund
Intrinsic events	Cost-related operations	Staff leave
		Equipment in bad condition
		Security incidents

Types	Sources	Possible affecting events
		Raw material abnormities
		Work in progress abnormities
	Quality-related operations	Wrong material supply
		Malfunction
		Equipment in bad condition
		Test error
	Delivery-related operations	Unqualified standard operating procedure (SOP) training
		Tools missing
		Power failure

Focus is on the manufacturing process, therefore, on the intrinsic operations. Representative feasible KPIs are selected for the plant performance evaluation according to the critical success factors, as shown in Table 3.3, which will be used for implementation in the following chapters.

Table 3.3 KPIs chosen for plant main performance evaluation

Type	Sources	Key performance indicators
Intrinsic KPIs	Cost-related KPIs	Worker efficiency
		Allocation ratio
		Asset depreciation
		Energy consumption level
		Inventory carrying ratio
		Overall equipment effectiveness (OEE) index
	Quality-related KPIs	Quality ratio
		Scrap ratio
		First pass yield
		Rework ratio

Type	Sources	Key performance indicators
	Delivery-related KPIs	Throughput rate
		Cycle ratio
		Delivery efficiency
		SOP ratio

The classifications of complex events and KPIs have distinguishing hierarchical characteristics, so it is convenient to use a hierarchical structure to make the analysis, as shown in Figure 3.4. The highest level, that is to say, the intrinsic KPIs, are referred as goal, the sub categories are referred to as criteria while the lowest level in this procedure are referred to as sub-criteria. To achieve a good performance of the goal, that is to say, intrinsic KPIs, it is necessary to have a full expression of the lowest sub-criteria level KPIs. The definition and calculation will be explained in next section.

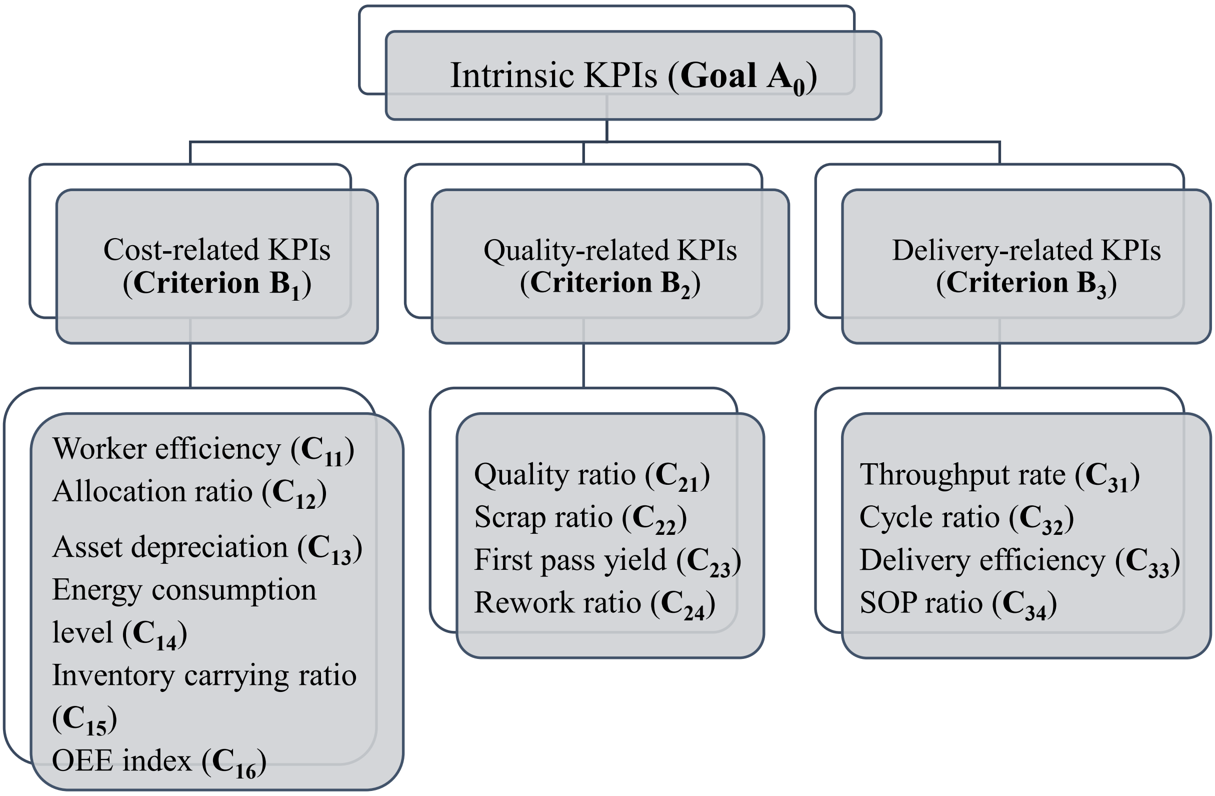

Figure 3.4 Hierarchical structure for fuzzy analysis

3.3. KPIs models and calculation formulas

Before calculating KPIs, it is essential to have an elaborate knowledge about the value-added process inside a plant. The elements involved in are personnel, orders, inventories, quantity and work units. First the time models for above elements are introduced, then KPIs are specified and calculated using these time models.

3.3.1. Element models to calculate KPIs

Work units are the basic composition of an enterprise, as shown in Figure 2.2, being equipment used for batch, discrete and continuous production or for storage as well as movement [4]. The time line for work units can be illustrated as shown in Figure 3.5. Actual production time is the very period that used for value-added process, and the differences between these periods has much to do with efficiencies. The dashed lines indicate inclusion relations of different times.

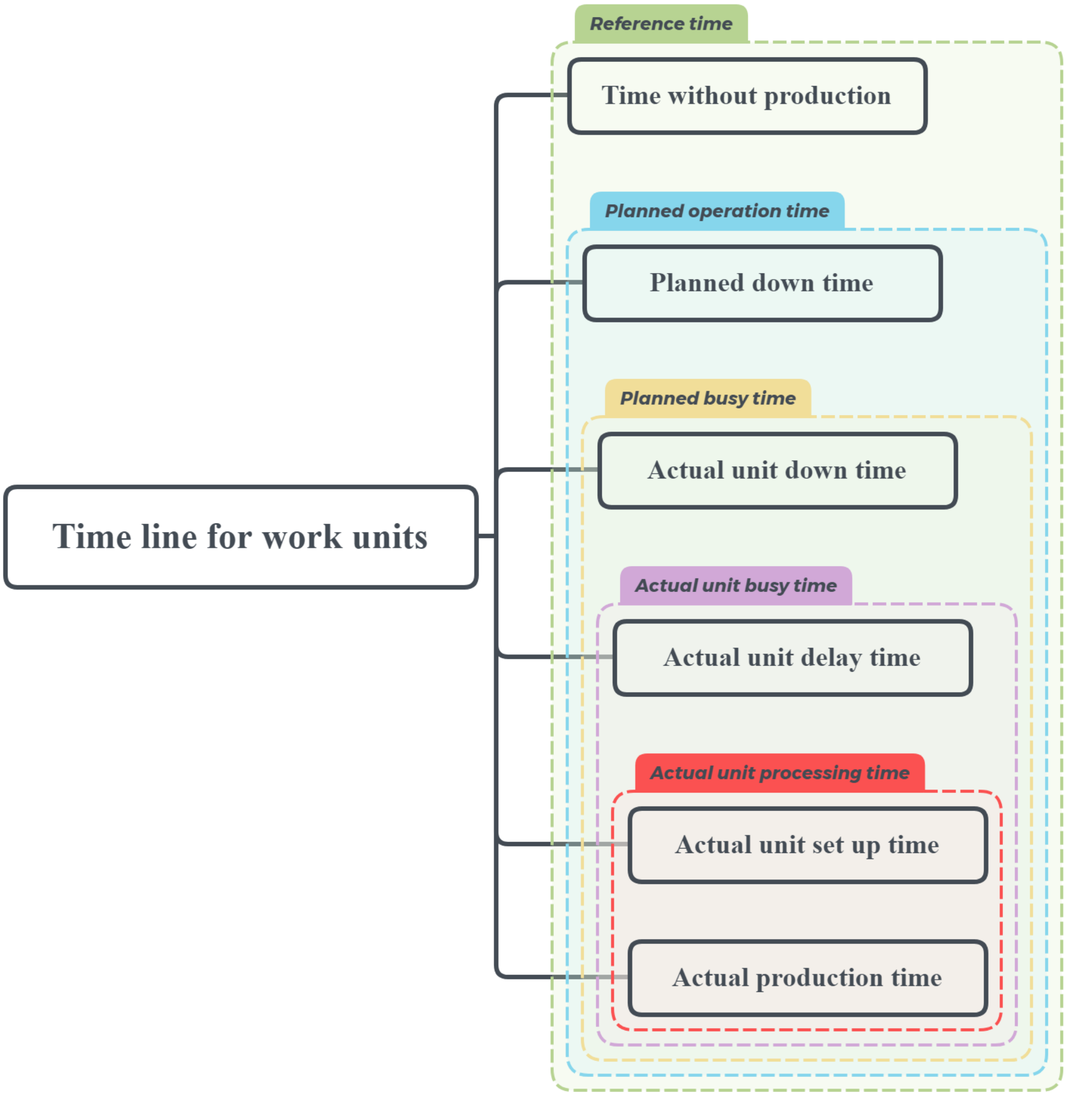

Figure 3.5 Time partitions partitions related to work units

Reference time is the calendar days without caring the production state. The planned operation time of a work unit consists of the time used for actual production, actual set up, actual delay and downtime. The higher proportion of actual production time means higher focus on the correct part. Setup time, delay time and downtime should be lowered to reduce unnecessary cost.

When it comes to production order processing, time line is represented as shown in Figure 3.6. Assuming n orders sequences, there are periods necessary for transporting and queueing, which must be taken into considerations. The sum of these betweentimes and processing time is actual unit busy time (AUBT). Time used for n order sequences are the actual order execution time. The dashed lines indicate inclusion relations of the represented periods, and contribute to KPIs calculations.

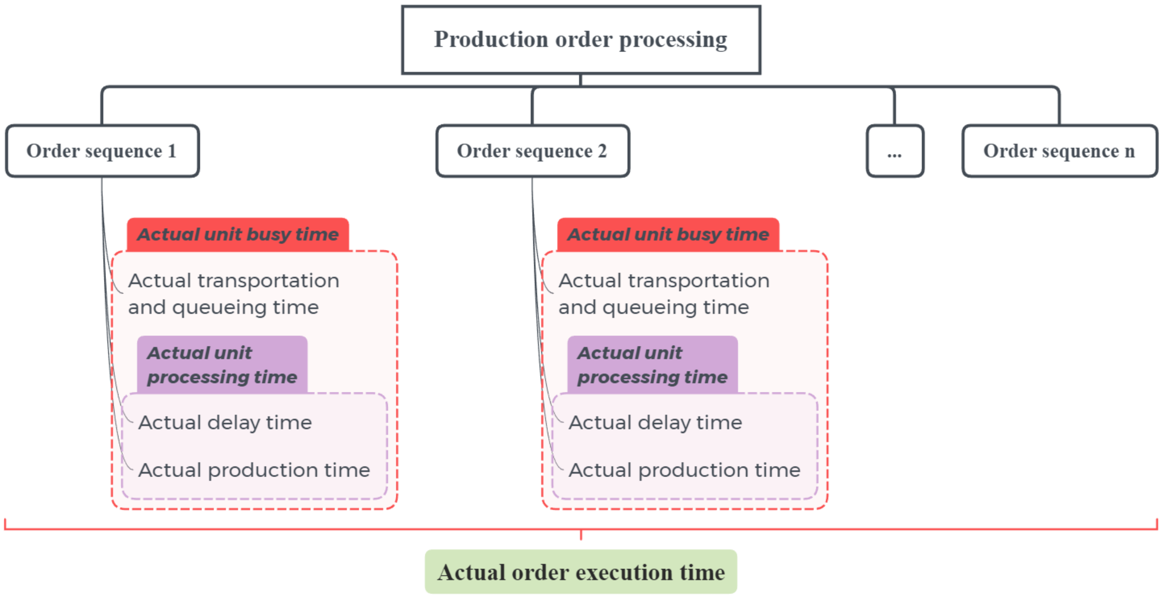

Figure 3.6 Time partitions related to production order

The produced quantity in a discrete manufacturing plant is composed of qualified goods, scrap quantity and quantity can be reworked or repaired, as shown in Figure 3.7, which can be used to evaluate quality ratio.

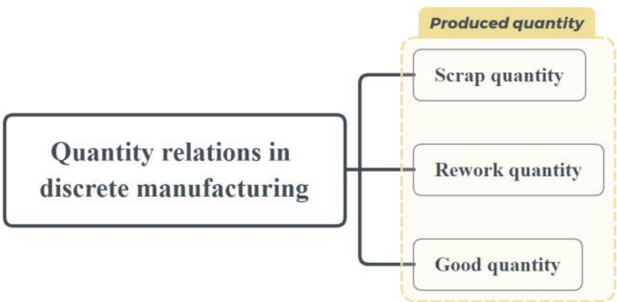

Figure 3.7 Quantity relaitons for discrete manufacturing plant

Last but not least, time line for staff is illustrated as shown in Figure 3.8. Reference time is the calendar days including legal working time and public holidays, while legal working time is not always fulfilled considering the possible absence. Then the actual wok time can be defined by exclude breaks like lunch time from the attendance time. Worker efficiency then can be derived.

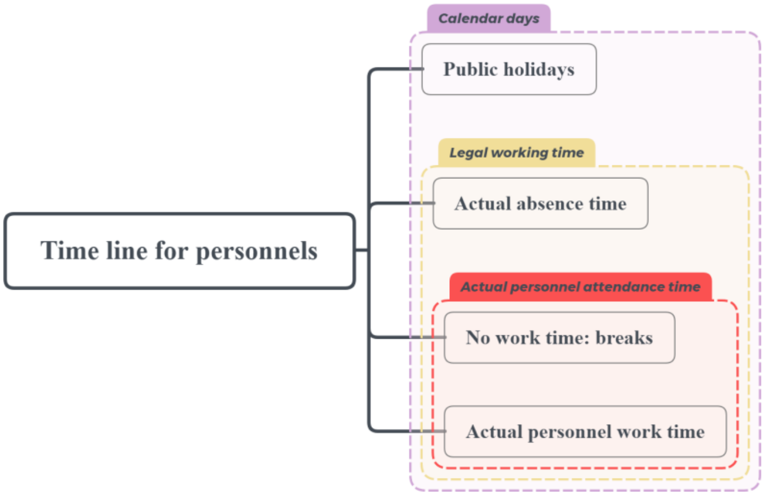

Figure 3.8 Time partitions related to personnel

Other than above element models, models for maintenance, inventories and so on can also be considered.

3.3.2. Calculation of selected KPIs

Cost-related KPIs are specified as worker efficiency, allocation ratio, overall equipment effectiveness index defined by *ISO 22400* and asset depreciation rate, energy consumption level, inventory carrying ratio defined under the consideration of the results of complex event progressing.

1) Worker efficiency is the relationship between the actual personnel work time (APWT) and the actual personnel attendance time (APAT). A worker doesn't work all the time because the characteristics of human being. The difference between them is breaks for meal or rest, which are necessary for reasonable operations and behaviours. The unit of worker efficiency is percentage, ranging from zero percent to one hundred percent. It is worth noting that working duration is not simply added by machine operation time since one worker can operate more than one machines. Calculation method of worker efficiency is expressed in equation (1).

$$worker\ efficiency = APWT/APAT \quad (1)$$

2) Allocation ratio is the proportion between sum of actual unit busy time (AUBT) and actual order execution time of a production order (AOET). The unit of allocation ratio is percentage, ranging from zero percent to more than one hundred percent. It can exceed one hundred percent because there could be more than one operation at the same time, and the summary of actual unit busy time can be larger than actual order execution time. Higher allocation ration means relatively lower idle time portion so as to higher produced quantity within a specific time interval.

The measure of allocation ratio is periodically. Formula to calculate allocation ratio is expressed in equation (2).

$$allocation\ ratio = \sum AUBT\ /AOET \tag{2}$$

3) Asset depreciation is a considerable parameter when evaluating cost in a plant, because it is more reasonable to distribute the equipment cost over a period of usage in stead of recoding it in the time of installation. Asset depreciation is defined as the ratio between depreciable cost and useful like of the asset. Depreciable cost can be obtained from the difference between asset total fixed cost and salvage value. The salvage value is the residual worth that can be obtained at the end of useful life. There are several methods to calculate asset depreciation amount, the simplest one, straight-line depreciation, is expressed in equation (3). Other than this method, declining balance depreciation and sum-of-the-years digits can also be applied [11]. The unit of asset depreciation amount could be euros per year or euros per month, depend on specific requirements, whose actual value may be affected by malfunction or maloperation.

$$asset\ depreciation = depreciable\ cost/useful\ life \tag{3}$$

4) Energy consumption level reflects directly the energy cost input during production, including electrical power, mechanical power, fuel and so on, defined as the ratio between planned energy consumption (PEC) and actual energy consumption (AEC). The unit of energy consumption level is percentage, the higher the value, the lower the cost. Planned energy consumption can be determined and adjusted by empirical methodology or calculations. Actual energy consumption is measured and can be affected by many aspects. For example, behaviours interrupting machine operations are very likely to lengthen operating time, so does the energy consumption; what's more, malfunctions can also increase energy consumption. If the energy consumption level is high, actions should be taken to keep cost in a reasonable range. Method to calculation energy consumption level is expressed in equation (4).

$$energy\ consumption\ level = PEC/AEC \tag{4}$$

5) Inventory carrying ratio describes the proportion of work in progress (WIP) inventory cost (IC) with respect to average IC. The unit of inventory carrying ratio is percentage, ranging from zero percent to less than one hundred percent. The evaluation of inventory carrying ratio is not definitely under all conditions. If the value is high, on one hand, it may indicate dull of sale and deficit; however, on the other hand, it may due to intentional accumulation of products foreseeing prices increase as a result of festival or other events. The measure of inventory carrying ratio can be periodically and real-time, and the optimal value should be adjusted all the time. Formula to calculate it is expressed in equation (5).

$$inventory\ carrying\ ratio = WIP\ IC/average\ IC \tag{5}$$

6) Overall equipment effectiveness (OEE) index is defined as the ratio between effective busy time (EBT) and planned busy time (PBT), where EBT is the planned equipment busy time consumed by qualified quantities production and PBT is the

equipment busy time expected to produce all quantities. EBT can be calculated by multiple number of good quantities by average planned time for each item production. The unit of OEE index is percentage, ranging from zero percent to one hundred percent, higher value indicating better efficiency of work units or work centers. The measurements can be carried out on-demand, periodically or real-time. Calculation method of OEE index is expressed in equation (6).

$$OEE\ index = EBT/PBT \tag{6}$$

Quality-related KPIs are specified as quality ratio, scrap ratio, first pass yield and rework ratio defined by *ISO 22400.*

1) Quality ratio is the most direct indicator of quality, defined as the proportion of good quantity with respect to overall production within a specific period. It reflects the performance of value-added process at the output without caring the details during the process like equipment states and operators' behaviours. Quality ratio is expressed by equation (7) whose unit is percentage. Quality ratio should be measured in real-time and a higher value means better performance of the production process.

$$quality\ ratio = good\ quantity/produced\ quantity \tag{7}$$

2) Scrap ratio is defined as the ratio between scrap quantity and produced quantity. Scrap quantity represents the number of products that cannot be repaired and must be scraped. The unit of it is percentage, ranging from zero to one hundred percent, indicating a higher quality. Formula to calculate scrap quality is expressed in equation (8).

$$scrap\ ratio = scrap\ quantity/produced\ quantity \tag{8}$$

3) First pass yield is defined as the ratio between the number of products without rework or scrap and the number of inspected parts. As we can see, unlike first pass yield, quality ratio is measured at the final step considering also products with rework. On the contrary, first pass yield is measured at each individual process and acts as an important parameter when evaluating process performance. This ratio ranges from zero percent to one hundred percent, where one hundred percent stands for a perfect production process. Formula to calculate first pass yield is expressed in equation (9), which can be executed on-demand, periodically or real-time.

$$first\ pass\ yield = good\ parts/inspected\ parts \tag{9}$$

4) Rework ratio is the proportion of quantity need to be reworked and total quantity produced. In quality inspection, there are several methods to deal with the unqualified products. Some of the unqualified ones can be reworked with a reasonable cost and delivered with good quantities, while for other unqualified ones, they are dealt with as scrap or waste as it is unworthy or impossible to fix them. The defectives of work in progress can also be found in processive procedures. Therefore, rework ratio in some extent indicates the quality and inspection precision. Equation (10) expresses the calculation method of rework ratio. The unit of rework ratio is percentage, ranging from zero percent to one

hundred percent. The measure of rework ratio could be on-demand, periodically as well as real-time for discrete, batch and continuous production.

$$rework\ ratio = rework\ quantity/produced\ quantity \tag{10}$$

Delivery-related KPIs are specified as throughput rate defined by *ISO 22400*, and cycle time ratio, delivery efficiency as well as standard operating procedure (SOP) ratio newly defined upon analysis in above chapters.

1) Throughput rate is an indicator of production capability, describing how many products can be processed within a specific period, which is AOET in this thesis. Inventory is the products hold in warehouse, and throughout rate is strongly associated to inventory, thus influences revenue directly. It is a fundamental term when considering delivery of a manufacturing plant. The unit of throughput rate is quantity unit per time unit; larger values generally stand for a better performance, while the quality ratio should be paid attention to. Formula to calculate throughput rate is expressed in equation (11).

$$throughput\ rate = produced\ quantity/AOET \tag{11}$$

2) Cycle ratio represents the relationship between actual cycle time (ACT) and planned cycle time (PCT). Cycle time of a manufacturing plant, similar to cash conversion cycle of a company, is defined as a period in which a specific amount of raw material is converted into finished products instead of cash. The PCT accounts for perfect production condition, what's more, it is estimated by empirical methodology. As shown in equation (12), the unit of cycle ratio is percentage and generally is larger one hundred percent. The more it approaches one hundred percent, the more ideal the process is.

$$cycle\ ratio = ACT/PCT \tag{12}$$

3) Delivery efficiency is the relationship between in-time deliveries and total deliveries. This parameter considers the unexpected delays of delivery, also influences on inventory turns. As we can see from equation (13), the unit of measure is percentage, and one hundred percent stands for ideal delivery states. Correct and in-time deliveries are important aspects when evaluating performance of a manufacturing plant.

$$delivery\ efficiency = in - time\ deliveries/total\ deliveries \tag{13}$$

4) SOP ratio is defined as the proportion of acceptable procedures performed over all procedures. This ratio is closely related to staff training as well as proficiency, and can be increased by improving training system and methods. SOP ratio is calculated by equation (14).

$$SOP\ ratio = times\ of\ SOP/total\ operating\ procedures \tag{14}$$

In summary, the 14 intrinsic KPIs are explained, then the methodology to implement KPIs is built in chapter 4.

4. KPIs implementation using fuzzy sets

The critical success factors and corresponding KPIs have been specified in chapter 3, which are derived from complex event progressing. As we can see, the complex events analyzed in a manufacturing plant is far away from independent, in other words, among which there are intricate relationships. The main logic relationships can be classified as time sequence relation, causality and hierarchical relation. Therefore, the integration and analysis of the main relations are the gateway to implement and apply the KPIs into practice.

The reason why the analysis is necessary can be stated mainly in two aspects. The first is for active safety, that is to say, to discover the potential harmful factors in the plant and apply actions to avoid abnormal events occurring before causing results. This can be achieved by analyzing and integrating the time sequence relation, causality and hierarchical relation among key operations or elements as well as corresponding KPIs, the result of which is to be compared with the previous production to understand the current production state so as to predict potential risks. By this way, it is possible for the plant to make fully preparation for the risks or even prevent risks from happening. The second reason is what is called passive safety, that is to say, tracking back to the source of affairs that already happened, to mitigate the consequence as well as to prevent recurrence. After incidences happening in a plant, if the causes cannot be known, it is even more difficult to solve the problem. By analyzing the main logic relations among the incidences, it is possible to find out quickly root causes and then measures can be adopted to look after the consequences and prevent similar incidences occurrence in the future.

However, the relationships are not always unambiguous and be represented by numbers, which can be solved by the introduction of fuzzy mathematics.

4.1. KPIs five-dimensional weighting

The analysis of logic relationships is in reality pointing out where the attention and focuses should be put by weighting related operations or elements. In this section, the weighting is to be done considering multiple dimensions.

4.1.1. Possible difficulties in implementation

It is not an easy work to integrate and implement KPIs in a system considering the following aspects. First, as we already seen, the performance of a manufacturing plant could be influenced by several events that are not independent, which needs a comprehensive and systematic of the three main logic relationships.

However, apart from this, there are more difficulties from other levels. The second is the difference in time frame between enterprise control level and production level. In the hierarchical enterprise structure, as what already stated, the time frame at business planning and logistics level is generally years or months, in corresponding to a long-term goal, while the time frame at manufacturing or production level, such as in a production line, is typically hours, minutes or even seconds, which are much smaller than that at business planning and logistics level. What’s more, another difficulty lies in the different focuses of ERP system and process control system. The decision-makers are plan to achieve a huge goal sustainably while the lower-level are more utilitarian and focusing on current benefits. This inconformity may cause the discrepancy of enterprise goal and short-term or individual targets, which is likely to imped enterprise development

On the other hand, the time delay when incidents occur can not be ignored. The current information system in plants is generally passive, waiting for operators to consult and determine what to do next, which means there is a time delay between the occurrence and handling. This deteriorate the efficiency of information processing and leads to additional cost

Last but not least, the complexity of disturbances and exceptional events have large influences. It's very difficult, or in other words, unworthy to monitor all the events at the same time. Also, the KPIs have mutual relationships which causes difficulties in the implementation. In a word, it is surely remarkable to implement and put into use KPIs.

4.1.2. Factors to be considered in implementation

The weighting of KPIs should focus on the value-added process, thus the factors affecting the process are specified. The following dimensions are derived from the three main logic relationships, time sequence relation, causality and hierarchical relation. Firstly, the significance and frequency of the event can be determined or estimated, then the event is divided into two types: predictable events and unpredictable events. A predictable event means precautions or preventive actions can be taken before or immediately after the event occurs. On the other hand, if an event is unpredictable, it's necessary to take the results into considerations, which can be represented as observability and time sensitivity. By considering above parameters, which are also shown in Figure 4.1, the weight can be obtained.

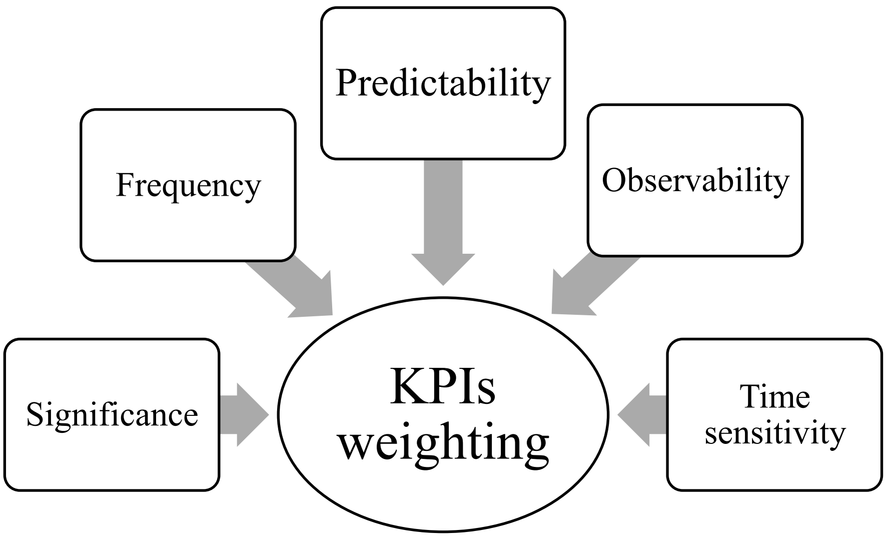

Figure 4.1 Five-dimensional KPIs weighting model

To confirm the weight of each KPI, five contributions are taken into considerations.

1) Significance. It's the importance of an event, especially when it has an effect on what happens in the future. It's the most direct contribution when applying weighting since large significance means large effect on plant production, i.e., the value-added process, which is a main goal of an enterprise.

2) Frequency. It's the rate at which one thing occurs or repeats. The more frequent, more attention should be concentrated, which means more contribution in the weighting.
3) Predictability. It indicates the quality of being predictable. If the predictability is high, the time delay between incidence occurrence and handling can be lowered, which means higher possibility to improve value-added process.
4) Observability. It specifies the capability to observe the relevant occurrences and repetitions. Higher observability means easier discover of the events, thus calls for higher attention.
5) Time sensitivity. It's related to the severity of time delay between incidence occurrence and handling. The higher time sensitivity, the more attention should be allocated.

The five contributions are implemented in the total weight by the means of coefficients characterized by membership degree functions which will be introduced detailly in the following sections.

4.1.3. Hierarchical process and fuzzy mathematics

The analytical hierarchical process (AHP) is a multi-attribute decision-making methodology, whose critical part is to establish comparison matrix by pairwise comparison, so as to obtain a priority vector. The hierarchy is composed of different levels, from the objectives, through varieties of criteria to set of alternatives [12]. This method can avoid left out of elements when we have large number of sub-attributes. The first step to achieve analytical hierarchical process is to modeling the complex event to be evaluated. It's convenient to decompose a complex event into several hierarchies when handling issues. The typical structure for analytical hierarchical process is three layers: goal, criteria and sub-criteria, which has been established as Figure 3.4. The second step is to make pairwise comparisons of elements at the same level It's recommended that the most suitable number of grading levels for human being is 7 ± 2; to compare the importance of two elements, a 9-level grading system is chosen. Number 1 to 9 are used to grade the importance. The number 1 stands for equal importance; the larger the number, the more the importance, till number 9 stands for the former element is absolutely important than the latter element. The opposite comparisons are realized by reciprocals, for example, 1/9 means that the latter element is absolutely important than the former one.

To obtaining the local priority vector, several methods such as least square methodology and harmonization methodology can be used. Then the consistency should be verified. The third step is then the obtain of final priority vector by separately multiply the lower-level local priority vector to the higher-level weight.

In reality, due to human subjectivity and linguistic uncertainties, the judgement is generally not exactly determined. The most important characteristic of human language is its ambiguity, which brings difficulties when trying to measure it uniformly with a classical mathematical model. Therefore, the measurement cannot be represented as a precise number, but an interval; fuzzy sets are introduced to comprehensively determine the subordinate states from many aspects. It's reasonable to express this relationship using membership degree function, defining to what degree one element is belonging to a classification. The fuzzy comprehensive evaluation method describes the fuzzy boundary by membership degree and is one of the most basic mathematical methods in fuzzy mathematics. An overall and clear evaluation of things that subject to various factors can be obtained by transforming qualitative evaluation into quantitative evaluation according to the membership degree fuzzy theory. What's more, a fuzzy hierarchical process takes into account the hierarchical nature of the objects as well as the human experiences, making the results more objective and realistic.

4.2. Significance

Significance of a KPI is the most important and direct parameter during the implementation. To weight significance reasonably, fuzzy mathematics are introduced.

4.2.1. Triangular fuzzy number

A triangular fuzzy number is expressed as shown in equation (15). The parameters l and m represent the degree of fuzzy in terms of judgement. Parameter l represents lower limit of the interval, which means the most conservative value, while parameter u stands for the most optimistic possible value, m stands for the most promising value.

$$M = (l, m, u) \tag{15}$$

The function of membership degree of a triangular fuzzy number is defined as shown in equation (16). There are three sections in total. The section between lower limit and the most promising value is incremental, with the membership degree equal to one at m, while the section between the most promising vale and upper limit is diminishing. Out of theses ranges, the value of membership degree always equal to zero, standing for null subordinate relation.

$$\mu_M(x) = \begin{cases} \frac{x-l}{m-l}, & l \leqq x \leqq m \\ \frac{x-u}{m-u}, & m \leqq x \leqq u \\ 0\ , & otherwise \end{cases} \tag{16}$$

A triangular fuzzy number can also be graphically represented as shown in Figure 4.2, and the plot does not have to be symmetric about m.

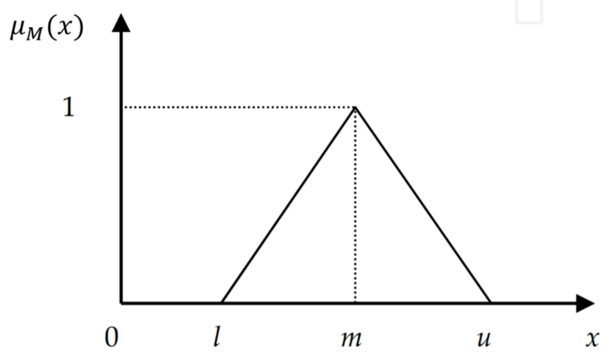

Figure 4.2 Triangular fuzzy number graphical representation

There are several operational rules for calculations of triangular fuzzy number. The most important is the reciprocal rule as shown in equation (17). Reciprocal of a triangular fuzzy number is composed by the reciprocal of upper limit, the reciprocal of the most promising value and the reciprocal of the lower limit.

$$M^{-1} = \left(\frac{1}{u}, \frac{1}{m}, \frac{1}{l}\right) \tag{17}$$

The addition of triangular fuzzy numbers is as shown in equation (18), equal to the separate summary of lower limits, the most promising values and upper limits maintaining its dimension.

$$M_1 + M_2 = (l_1 + l_2, m_1 + m_2, u_1 + u_2,) \tag{18}$$

The distance between two triangular fuzzy numbers can be defined as shown in equation (19). When two numbers are identical, the similarity as shown in equation (20) is equal to one.

$$distance(M_1, M_2) = \left\{\frac{1}{3}[(l_1 - l_2)^2 + (m_1 - m_2)^2 + (u_1 - u_2)^2]\right\}^{0.5} \tag{19}$$

$$similarity(M_1, M_2) = 1 - \frac{1}{3}[|l_1 - l_2| + |m_1 - m_2| + |u_1 - u_2|] \tag{20}$$

The expectation calculations of a triangular fuzzy number, or in other words, the means to transform a triangular fuzzy number into a real number, the so-called defuzzification, are various. The purpose of this procedure is to compare sizes of triangular fuzzy numbers. One way is considering the average area contained by the corresponding graphical representations. The second way is to compare the means as well as variances. Another approach is to compare the degree of possibility of two arbitrary triangular fuzzy number. The last methodology introduced in this thesis takes into account the attitude of judgement, with a new parameter μ. This coefficient is multiplied separately by left expectation and right expectation. If the judger is positive about the factor, $\eta < 0.5$, and $\eta = 0.5$ for neutral attitude, $\eta > 0.5$ for negative attitude. The expectation calculation is expressed as shown in equation (21).

$$E(\mu) = \eta \times \frac{l+m}{2} + (1 - \eta) \times \frac{m+u}{2} \tag{21}$$

4.2.2. Pairwise comparison matrix

After triangular fuzzy number is introduced, Delphi method is applied to obtain pairwise comparison matrixes. The Delphi method is devised to obtain consensus among experts through an iterative procedure over several questionnaires [2]. Along with the questionnaire priority vectors can be derived. Similar to AHP, the grades in fuzzy AHP are as shown in Table 4.1.

Table 4.1 Correspondence between AHP grading and fuzzy AHP grading

Importance comparison of 2 elements	AHP		Fuzzy AHP	
	Initial	Reciprocal	Initial TFN	Reciprocal TFN
The two are equally important	1	1	(1,1,1)	(1,1,1)

Importance comparison of 2 elements	AHP		Fuzzy AHP	
	Initial	**Reciprocal**	**Initial TFN**	**Reciprocal TFN**
Intermediate between 2 adjacent scales	2	$\frac{1}{2}$	(1,2,3)	$\left(\frac{1}{3},\frac{1}{2},1\right)$
The former is weakly more important than the latter	3	$\frac{1}{3}$	(2,3,4)	$\left(\frac{1}{4},\frac{1}{3},\frac{1}{2}\right)$
Intermediate between 2 adjacent scales	4	$\frac{1}{4}$	(3,4,5)	$\left(\frac{1}{5},\frac{1}{4},\frac{1}{3}\right)$
The former is fairly more important than the latter	5	$\frac{1}{5}$	(4,5,6)	$\left(\frac{1}{6},\frac{1}{5},\frac{1}{4}\right)$
Intermediate between 2 adjacent scales	6	$\frac{1}{6}$	(5,6,7)	$\left(\frac{1}{7},\frac{1}{6},\frac{1}{5}\right)$
The former is strongly more important than the latter	7	$\frac{1}{7}$	(6,7,8)	$\left(\frac{1}{8},\frac{1}{7},\frac{1}{6}\right)$
Intermediate between 2 adjacent scales	8	$\frac{1}{8}$	(7,8,9)	$\left(\frac{1}{9},\frac{1}{8},\frac{1}{7}\right)$
The former is extremely more important than the latter	9	$\frac{1}{9}$	(9,9,9)	$\left(\frac{1}{9},\frac{1}{9},\frac{1}{9}\right)$

In a hierarchical process, as stated before, there are three layers, goal, criteria and sub-criteria. The procedure of Delphi method can be graphically expressed as shown in Figure 4.3. Assuming there are m criteria, and n sub-criteria for each criterion, then t experts are invited to make independent judgements, obtaining n-order pairwise comparison matrixes. Each expert has its weight on the base of knowledge and empirical value, forming a matrixes of experts' weight for implementing.

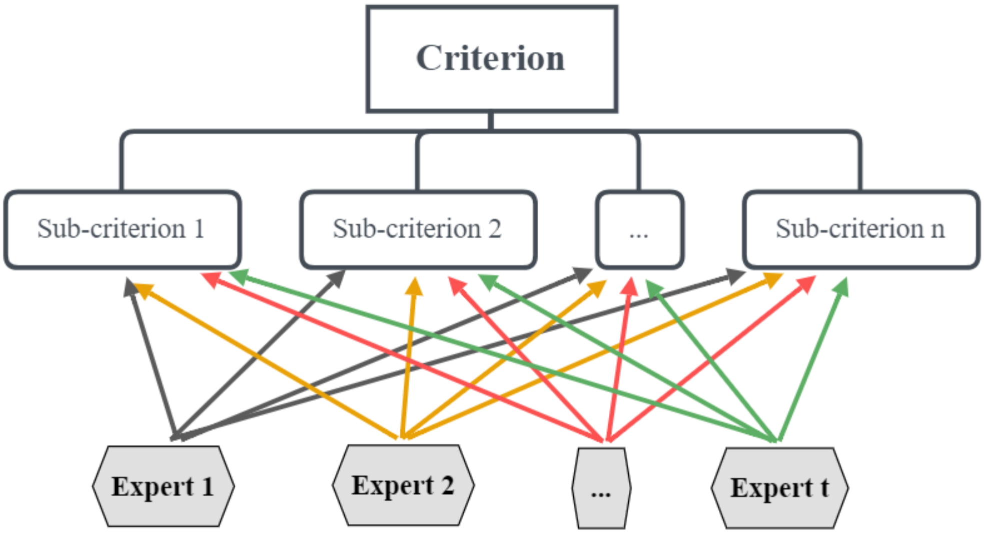

Figure 4.3 Delphi method to make pairwise comparisons

Therefore, the number of times that each expert should do pairwise comparison judgements for each criterion is as shown in equation (22). n stands for the number of sub-criteria with respect to its upper level.

$$number\ of\ times = n \times (n-1)/2 \tag{22}$$

The appropriateness of experts' selection has effect on the precision of weighting. After obtaining the comprehensive result, it is necessary to feedback results to experts, who may adjust their pairwise comparisons until a consistent result is achieved, in that case the consistency check should be verified.

Therefore, the comparison results of i^{th} and j^{th} sub-criteria can be expressed using the triangular fuzzy number shown in equation (23). The comparison result between two arbitrary same elements is identical.

$$M_{ij} = \left(l_{ij}, m_{ij}, u_{ij}\right), \quad i = 1,2,\dots,n; \; j = 1,2,\dots,n \tag{23}$$

Considering k^{th} expert, the pairwise comparison judgement matrix can be expressed by equation (24).

$$M^{(k)} = (M_{ij}^{(k)})_{n\times n}, \quad k = 1,2,\dots,t \tag{24}$$

And each element in the matrix has the expression as shown in equation (25).

$$\left(M_{ij}^{(k)}\right) = (l_{ij}^{(k)}, m_{ij}^{(k)}, u_{ij}^{(k)}) \tag{25}$$

The elements in pairwise comparison has the relationship as shown in equation (26) considering the definition of reciprocal shown in equation (17). Thus, the matrix can be put into computation.

$$l_{ji}^{(k)} = \frac{1}{u_{ij}^{(k)}}, m_{ji}^{(k)} = \frac{1}{m_{ij}^{(k)}}, u_{ji}^{(k)} = \frac{1}{l_{ij}^{(k)}} \tag{26}$$

Considering also the priority matrix of the t experts which can be determined by their knowledge, experience and so on, as shown in equation (27).

$$Ex^{(t)} = (e_1, e_2, \dots, e_k, \dots e_t)_{1\times t}, \quad e_k = (l_k, m_k, u_k) \tag{27}$$

Therefore, the integrated matrix M for a criterion evaluated by t experts with n sub-criteria is obtained and expressed as shown in equation (28), taking the weight vector of experts into consideration.

$$M_{ij} = \left(l_{ij}, m_{ij}, u_{ij}\right) = \frac{1}{\sum_{k=1}^{t} e_k}\left[\sum_{k=1}^{t}\left(l_{ij}^{(k)}, m_{ij}^{(k)}, u_{ij}^{(k)}\right) \times e_k\right] \tag{28}$$

The next step is defuzzification of the triangular fuzzy number. From the method considering experts' attitudes, a non-fuzzy matrix $A' = \left(a'_{ij}\right)_{(n\times n)}$ can be obtained using the formula expressed in equation (29) according to equation (21). The expectations of each triangular fuzzy number are the corresponding new elements of the non-fuzzy matrix.

$$a'_{ij} = \mathrm{E}(\mu) = \eta \times \frac{l_{ij}+m_{ij}}{2} + (1-\eta) \times \frac{m_{ij}+u_{ij}}{2} \tag{29}$$

To ensure that A' is a reciprocal matrix [19] for following calculations, it's necessary to adjust its elements so that $a_{ij}a_{ji} = 1$ for any $i = 1,2,\dots,n; j = 1,2,\dots,n$. The adjustment can be operated following the equation (30).

$$a_{ij} = \frac{a'_{ij}}{\sqrt{a'_{ij}a'_{ji}}} \tag{30}$$

4.2.3. Consistency check

Consistency check is necessary to ensure the validity of pairwise comparison matrix, avoiding situations that A is more important B, B is more important than C while C is more important than A. The criterion for consistency check is achieved by consistency ratio (CR). CR can be obtained from consistency index (CI) and random index (RI), where CI is derived from the maximum eigenvalue of the matrix λ_{max} as shown in equation (31), and RI is related to the order of matrix with the relationship shown in Table 4.2.

$$C.I. = \frac{\lambda_{max} - n}{n-1}, \quad \textit{n is the order of matrix} \tag{31}$$

Table 4.2 Random index limits

Matrix dimension	1	2	3	4	5	6	7	8	9	10	11
Random index	0	0	0.52	0.89	1.12	1.26	1.36	1.41	1.46	1.49	1.52

Finally, the value of CR can be obtained with the expression (32). Consistency check should be done to each comparison matrixes. If CR is smaller than 0.1, the matrix is validated; otherwise the experts need to adjust their judgements. This process shall be repeated until the CR limit is satisfied.

$$CR = CI/RI \tag{32}$$

4.2.4. Priority vector of a reciprocal matrix

Priority vector of a reciprocal matrix describes the relative importance of all same-level elements with respect to the upper level, for example, the relative priority of each criterion in terms of the goal. Priority vector can be realized by several methods, such as harmonization method, least square method and eigen value method. Harmonization method widely used and has two computing method. One is expressed as shown in equation (33) and another one is shown in equation (34).

$$w_i = \frac{1}{n}\sum_{j=1}^{n} \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \tag{33}$$

$$w_i = \frac{\sum_{j=1}^{n} a_{ij}}{\sum_{i=1}^{n}\sum_{j=1}^{n} a_{ij}} \tag{34}$$

Another method to obtain priority is least square method, as shown in equation (35).

$$w_i = \frac{\left(\prod_{j=1}^{n} a_{ij}\right)^{1/n}}{\sum_{i=1}^{n}\left(\prod_{j=1}^{n} a_{ij}\right)^{1/n}} \tag{35}$$

Eigen value method is as shown in equation (36), the priority vector being the eigenvector corresponding to the maximum eigenvalue λ_{max}.

$$Aw = \lambda_{max} w, \quad \sum_{i=1}^{n} w_i = 1 \tag{36}$$

Therefore, the total significance vector can be obtained by multiply respectively the priority of sub-criteria to that of each criterion considering m criteria and n sub-criteria, as shown in equation (37), the significance vector obtained.

$$S = (s_{ij})_{((n\times m)\times 1)}, \quad s_{ij} = w_i \times w_{ij}, \quad i = 1,2,\dots,m; j = 1,2,\dots,n \tag{37}$$

4.3. Frequency, predictability, observability and time sensitivity

Frequency is defined as the occurrence rate of one thing. The fuzzy part is to determine to what degree the occurrence rate is belong to a specific linguistic expression, which can be obtained by questionnaire for example designed in appendix: determined to what degree 1 time per year is belonging to the expression extremely low. Membership degree function is then defined so as to transforming linguistic expressions into numerical expressions. The values of frequency parameter are specified in Table 4.3.

Table 4.3 Frequncy linguistic expression and corresponding numerical expressions

Occurrence rate	Frequency parameter
Extremely high	1
High	0.8
General	0.6
Low	0.4
Extremely low	0.2
Intermediate rate	0.9, 0.7, 0.5, 0.3

The frequency parameters can be expressed as a vector shown in equation (38), corresponding to complex events that corresponding critical KPIs in the manufacturing plants.

$$F = (f_i)_{((n\times m)\times 1)} \tag{38}$$

Predictability is the quality of an event being predicted. The fuzzy part is to determine to what degree the fact that time interval between incidence occur and awareness is belonging to a specific linguistic expression such as extremely predictable, impossible predictable as stated in the example questionnaire designed in appendix. The values of predictability parameters are expressed in Table 3.1. The possible membership degree function can be exponential type, as shown in equation (39), whose coefficient k depends on actual situations.

$$\mu_P(x) = \begin{cases} 0\ , & x < a \\ \left(\frac{x-a}{b-a}\right)^k, & a \leqq x \leqq b \\ 1\ , & x > b \end{cases} \tag{39}$$

Table 4.4 Predictability linguistic expression and corresponding paramter

Capability to predict	Predictability parameter
Extremely easy	1
Easy	0.8
General	0.6
Difficult	0.4
Extremely difficult	0.2
Intermediate capabilities	0.9, 0.7, 0.5, 0.3

The vector of predictability parameter can be therefore obtained using the similar approaches and expressed by equation (40).

$$P = (p_i)_{((n\times m)\times 1)} \tag{40}$$

Similar questionnaire and methodologies are used for observability and time sensitivity. Observability can be characterized by the time interval between an event occurrence and event handling, as shown inTable 4.5. Larger interval means lower capacity to find out, that is to say, to observe the event.

Table 4.5 Observability linguistic expression and corresponding numerical expressions

Capability to observe	Observability parameter
Extremely high	1
High	0.8
General	0.6
Low	0.4
Extremely low	0.2
Intermediate rate	0.9, 0.7, 0.5, 0.3

Time sensitivity can be characterized by the result severity along time axles. Larger time sensitivity requires more urgent handling, so larger weighting contribution, as shown in Table 4.6.

Table 4.6 Time sensitivity linguistic expression and corresponding numerical expressions

Severity of time delay	**Time sensitivity parameter**
Extremely high	1
High	0.8
General	0.6
Low	0.4
Extremely low	0.2
Intermediate rate	0.9, 0.7, 0.5, 0.3

Observability and time sensitivity use the same model of predictability, but with different index k. The two parameters are expressed as vectors shown in equation (41) and equation (42).

$$O = (o_i)_{((n\times m)\times 1)} \quad (41)$$

$$T = (t_i)_{((n\times m)\times 1)} \quad (42)$$

4.4. KPIs total weighting in five-dimensional model

For predictable and unpredictable event, the weight is calculated as shown in equation (43).

$$V(i) = \begin{cases} SF, & if\ the\ event\ is\ predictable \\ SFOT, & if\ the\ event\ is\ unpredicatble \end{cases} \quad (43)$$

Predictability is the possibility that the event is predictable, therefore, the expected value of weight is as expressed in equation (44).

$$E(V) = SFP + SFOT(1 - P) \quad (44)$$

By ranking the weight vector, the goal, that is to say, the plant's KPI, can be obtained, thus the performance evaluation of a plant is completed, according to which the optimization could be done to improve the value-added process.

5. Case study: steam explosion process

Nowadays, with the growing shortage of global energy and pollution of environment, the exploitation of clean and renewable power such as wind energy and bio-energy, has become the general trend. How to transfer the huge amount of agriculture waste like sugarcane and corncob into useful material and energy has been paid much attention.

One way is the decomposition of lignocellulose. Wood fiber contains three main compositions, cellulose, lignin and hemicellulose, which can be processed further to add value to them. For example, the high-value-added products functional sugar, feeding staff, cultivation bags and even graphene can be obtained. The procedure to separate these three compositions is called preprocess technics, including mechanical methodology, physical-chemical methodology and chemical methodology. The reality of these methodologies is to break the chemical bound formed by lignin and hemicelluloses.

Steam explosion process is one of the physical-chemical preprocess technics, which has the advantages of short processing time, low pollutant emissions, low energy consumption and so on, being developed quickly recent years [15].

5.1. Selection of critical elements

The main steps to achieve steam explosion process can be sketched simply as Figure 5.1. the purpose of this pretreatment procedure is to achieve degradation of wood fiber bundles for further processing. Therefore, the evaluation of steam explosion process should focus on the capability to provide qualified intermediate product for next procedure for example the production of functional sugar.

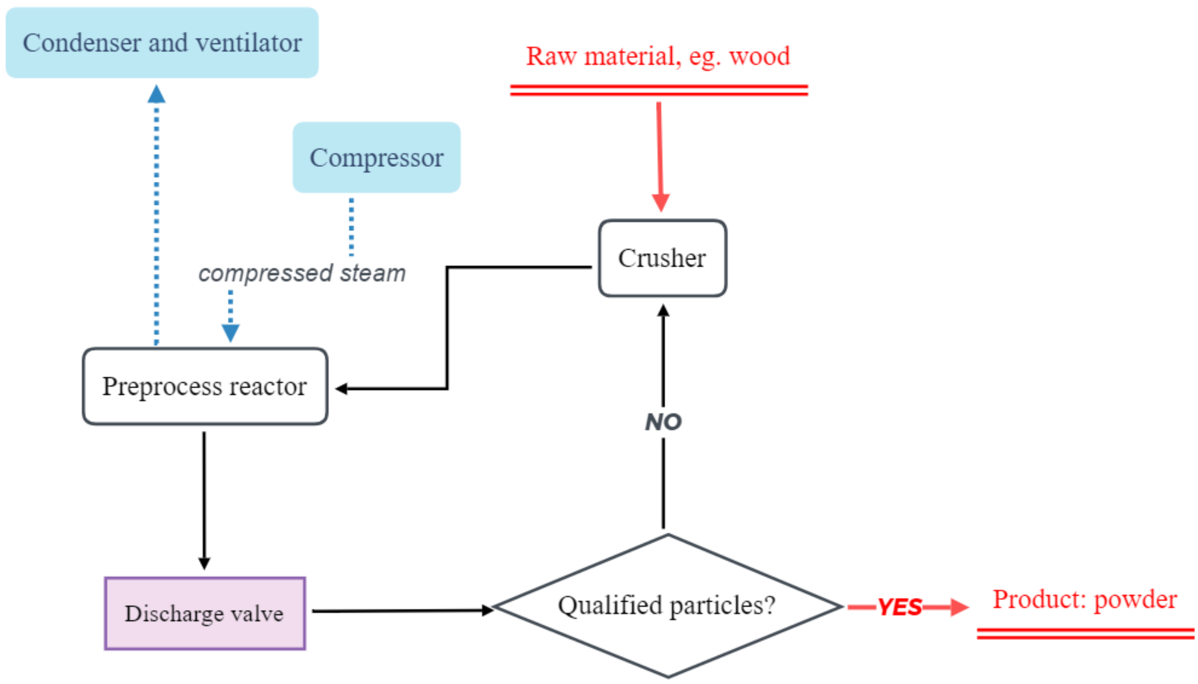

Figure 5.1 Procedures of steam explosion process

In steam explosion process, raw material, which is wood in this case, is broken up to small pieces in crusher, then is transmitted into preprocess reactor where the steam explosion is performed. There are two main stages of steam explosion process, in the first stage, wood pieces are maintained for a time interval at high temperature and pressure, compressed steam entering the cracks of material, transforming hemicellulose to soluble sugar and softening lignin. The second stage is discharge. The sudden release of high pressure drags steam molecule out of the material at very high speed, which breaks and rearranges the hydrogen bond, changing its chemical properties. If the products are qualified, that is to say, have the required properties, they are transmitted to the next process, otherwise the steam explosion process is repeated until requirements are met.

Applying complex event progressing illustrated in Figure 3.2, the disturbances, exceptions and uncertainties in steam explosion process can be specified. Followed by critical success factors analyzing, the critical operations and elements are verified as shown Table 5.1. For exterior sources, the quality of wood is the very critical success factor in terms of upstream procedure, due to the fact that various wood types have different characteristics, such as moisture content, fiber morphology and composition, which have great impact on the product quality. With regard to downstream procedure, unqualified quality control process may cause rejection.

Table 5.1 Events affecting steam explosion process

Types	**Sources**	**Possible affecting events**
Exterior	Upstream procedure	Raw material quality (wood types, etc.)
		Correctness of dispatch
	Downstream procedure	Reject or refund of products
Intrinsic	Cost-related operations	Abnormal energy consumption
		Equipment maintenances
		Labor absences and proficiency
		Equipment amortization
	Quality-related operations	Malfunction or maloperation
		Testing error
		Equipment bad working condition
	Delivery-related operations	Power failure
		Operators bad performance
		Tool missing

When it comes to intrinsic type, the critical operations are divided into cost-related, quality-related and delivery-related and are mainly selected on the basis of five elements, personnel, orders, inventories, energy and work units. Considering cost, the main contribution comes from hiring employees, energy consumed such as by air compressor and screw convey, crusher, equipment cost and so on. With regard to quality, the operations and incidences that may affect quality ratio such as malfunction and maloperation must be taken into considerations. As for delivery, a correct and efficient delivery should be satisfied to improve the value-added process. In conclude, from Table 5.1, KPIs can be selected as shown in Table 5.2. In this case only KPIs in manufacturing plant, that is to say, intrinsic KPIs, are considered, and they are structured hierarchically to three layers, goal, criteria and sub-criteria. In sub-criteria layer, 11 KPIs are selected and were defined in chapter 3. The goal of steam explosion process is to optimize the value-added process, to which the sub-layers work together to contribute.

Table 5.2 KPIs chosen for steam explosion process

Goal (A_0)	**Criteria (B_i)**	**Sub-criteria (C_{ij})**
Intrinsic KPIs (**A_0**)	Cost-related KPIs (**B_1**)	Worker efficiency (**C_{11}**)
		Asset depreciation rate (**C_{12}**)
		Energy consumption level (**C_{13}**)
		Inventory carrying ratio (**C_{14}**)
		OEE index (**C_{15}**)
	Quality-related KPIs (**B_2**)	Quality ratio (**C_{21}**)
		First pass yield (**C_{22}**)
		Rework ratio (**C_{23}**)
	Delivery-related KPIs (**B_3**)	Throughput rate (**C_{31}**)
		Cycle ratio (**C_{32}**)
		Delivery efficiency (**C_{33}**)

Once the 11 KPIs are extracted, its weighting can be analyzed with the implementation of five parameters, significance, frequency, predictability, observability and time sensitivity.

5.2. Model implementation

After selecting KPIs of the steam explosion process, four experts are invited to fill in the questionnaires for significance designed in the appendix, whose results are as shown in Table 5.3. The pairwise comparisons of four experts are converted into triangular fuzzy numbers according to Table 4.1. Then the addition rule of triangular fuzzy number expressed by equation

(18) is used to integrate the four numbers as one, and the results are shown in Table 5.4, that is to say, the significance pairwise comparison matrixes among cost-related, quality-related and delivery related KPIs with respect to intrinsic sources.

Table 5.3 Experts evaluation data collected from questionnaires

	Cost-related vs. quality-related	Cost-related vs. delivery-related	Quality-related vs. delivery-related
Expert 1	(1,2,3)	(2,3,4)	(2,3,4)
Expert 2	(1,2,3)	(1,2,3)	(1,1,1)
Expert 3	(1,1,1)	(1,2,3)	(1,2,3)
Expert 4	(1,2,3)	(1,2,3)	(1,2,3)

The consistency check should be done to ensure validity and reliability of experts' appraises, otherwise experts are supposed to reconsider the judgements carefully and adjust them. On the ground of triangular fuzzy number addition rule, the integrated results are just arithmetical average of four numbers.

Table 5.4 Pairwise comparison matrix of elements for intrinsic KPIs

Criteria level	B_1	B_2	B_3
B_1	(1.00,1.00,1.00)	(1.00,1.75,2.50)	(1.25,2.25,3.25)
B_2	(0.40,0.57,1.00)	(1.00,1.00,1.00)	(1.25,2.00,2.75)
B_3	(0.31,0.44,0.80)	(0.36,0.50,0.80)	(1.00,1.00,1.00)

Taking the experts' attitude whose data collected also from the questionnaires into consideration, expectations are obtained by equation (21). Next, in order to ensure that the matrix is reciprocal, equation (30) is applied and the results are shown in Table 5.5.

Table 5.5 Reciprocal matrix for criteria-level KPIs with respect to goal level

Criteria level	B_1	B_2	B_3
B_1	1.0000	1.6592	2.1231
B_2	0.6027	1.0000	1.9229
B_3	0.4710	0.5201	1.0000

There are several methodologies to compute priority vector of a reciprocal matrix, such as harmonization, least square method and eigen value method. The priority vector in this matrix is calculated by software MATLAB, and the program is shown in Figure 5.2. Methodology used is eigen value method. It is the eigen vector that corresponding to the maximum eigen value represents its priority vector. What’s more, the result vector should be normalized or standardized for convenience.

```
A=xlsread('D:\OneDrive - business\FINAL\Thesis\original data.xlsx',5,'U24:W26');
[~,sizeA]=size(A);
[x,y]=eig(A);
lamda_A=max(diag(y));

[maxy,m]=find(y==max(max(y))); % search for the maximum eigen
                                % value and corresponding eigen vector;
WA=x(:,m)/sum(x(:,m)); % standardization of priority vector;
disp('weight vector WA');disp(WA);
```

Figure 5.2 MATLAB code to compute priority vector

It is worth noting that the consistency check should always be done to ensure the validity of the data. This step can also be completed by MATLAB, and the code is shown in Figure 5.3, applying equation (31) and (32).

```
RI=[0 0 0.52 0.89 1.12 1.26 1.36 1.41 1.46 1.49 1.52 1.54 1.56 1.58 1.59];
CI=(lamda_A-sizeA)/(sizeA-1);
CR=CI/RI(sizeA);
disp('CI is');disp(CI);
disp('CR should < 0.1');disp(CR);
```

Figure 5.3 MATLAB code to do consistency check

The result of consistency check and priority vetor are shown in Figure 5.4. As is shown the consistency check is satisfied.

```
weight vector WA
    0.4758
    0.3285
    0.1957

CI is
    0.0092

CR should < 0.1
    0.0177
```

Figure 5.4 Priority vector for criteria-level KPIs and result of consistency check

Also, the data of pairwise comparisons among cost-related KPIs with respect to upper level are collected from questionnaires and integrated to a single triangular fuzzy number, as shown in Table 5.6. Consistency checks are done for each expert’s evaluation for the sake of validity. Then, the triangular numbers are converted into real numbers by considering attitude parameters. With similar procedures, reciprocal matrix is obtained and then priority vector can be acquired, so does the result of consistency check, as shown in Figure 5.5.

Table 5.6 Pairwise comparison matrix for cost-related KPIs

	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}
C_{11}	(1,1,1)	(2,3,4)	(1,1.25,1.5)	(1.5,2.25,3)	(0.83,1.125,1.5)
C_{12}	(0.25,0.33,0.5)	(1,1,1)	(0.67,0.75,1)	(0.67,1,1.5)	(0.48,0.58,0.88)
C_{13}	(0.67,0.8,1)	(1,1.33,1.5)	(1,1,1)	(1,1.25,1.5)	(0.83,1.13,1.5)
C_{14}	(0.33,0.44,0.67)	(0.67,1,1.5)	(0.67,0.8,1)	(1,1,1)	(0.25,0.33,0.5)
C_{15}	(0.67,0.89,1.2)	(1.14,1.71,2.09)	(0.67,0.89,1.2)	(2,3,4)	(1,1,1)

```
weight vector WA
    0.2900
    0.1314
    0.2042
    0.1256
    0.2489

CI is
    0.0244

CR should < 0.1
    0.0218
```

Figure 5.5 MATLAB results for cost-related KPIs

By the same method, matrixes for quality-related and delivery-related KPIs can be obtained, and the results are shown in Table 5.7

Table 5.7 Pairwise comparison matrixes for quality-related and delivery-related KPIs

	C_{21}	C_{22}	C_{23}
C_{21}	(1,1,1)	(0.67,0.75,1)	(1,1.75,2.5)
C_{22}	(1,1.33,1.5)	(1,1,1)	(1.25,2,2.75)
C_{23}	(0.4,0.57,1)	(0.36,0.5,0.8)	(1,1,1)

	C_{31}	C_{32}	C_{33}
C_{31}	(1,1,1)	(1,1.75,2.5)	(1.25,2.25,3.25)
C_{32}	(0.4,0.57,1)	(1,1,1)	(1,1.5,2)
C_{33}	(0.31,0.44,0.8)	(0.5,0.67,1)	(1,1,1)

Then, the priority vectors and results of consistency check are computed as shown in Figure 5.6. It is obvious that the consistency checks are all passed because consistency ratios are smaller than 0.1.

```
weight vector WA
    0.3498
    0.4325
    0.2177

CI is
   5.2557e-04

CR should < 0.1
    0.0010
```

```
weight vector WA
    0.4807
    0.3024
    0.2169

CI is
   9.1848e-04

CR should < 0.1
    0.0018
```

Figure 5.6 MATLAB results for quality-related and delivery-related KPIs

Next step is to compute the significance priority vector of each sub-criteria level KPIs with respect to the goal level by equation (37), as shown in last column in Table 5.8.

Table 5.8 Significance priority vector S

Goal level	Criteria level		Sub-criteria level		Significance priority vector S
	Types	Local priority vector	Elements	Local priority vector	
Intrinsic KPI (A_0)	Cost-related KPIs (B_1)	0.4758	C_{11}	0.2900	0.1380
			C_{12}	0.1314	0.0625
			C_{13}	0.2042	0.0972
			C_{14}	0.1256	0.0598
			C_{15}	0.2489	0.1184
	Quality-related KPIs (B_2)	0.3285	C_{21}	0.3498	0.1149
			C_{22}	0.4325	0.1421
			C_{23}	0.2177	0.0715
	Delivery-related KPIs (B_3)	0.1957	C_{31}	0.4807	0.0941
			C_{32}	0.3024	0.0592
			C_{33}	0.2169	0.0424

As we can see from Table 5.8, in terms of intrinsic source, cost is the most significant part in manufacturing plants performance evaluation, with the portion of 47.58%, followed closely by quality. When it comes to the lowest level, worker efficiency and OEE index play important roles with respect to cost-related KPIs, while the most significant one with respect to intrinsic source is first pass yield, then the worker efficiency and energy consumption level. After the significance parameter is acquired, the following four parameters are supposed to be computed.

At sub-criteria level, each KPI corresponds to one or more complex events which could be characterized by frequency, predictability, observability and time sensitivity. The characteristics of these events are implemented with real numbers according to the rules for transforming linguistic expressions into mathematical expressions. The data are collected by questionnaires designed in appendix. Results are as shown in Table 5.9.

Table 5.9 Weighting of sub-criteia level events with respect to goal level

Events features / Elements	Significance	Frequency	Predictability	Observability	Time sensitivity	Normalized weight
Worker efficiency (C_{11})	0.1380	0.4	0.3	0.9	0.9	26.96%
Asset depreciation rate (C_{12})	0.0625	0.1	0.8	0.6	0.6	3.07%
Energy consumption level (C_{13})	0.0972	0.2	0.3	0.8	0.8	8.19%
Inventory carrying ratio (C_{14})	0.0598	0.2	0.3	0.6	0.6	3.72%
OEE index (C_{15})	0.1184	0.3	0.6	0.6	0.8	15.85%
Quality ratio (C_{21})	0.1149	0.2	0.6	0.5	0.8	9.84%
First pass yield (C_{22})	0.1421	0.2	0.6	0.8	0.9	14.21%
Rework ratio (C_{23})	0.0715	0.2	0.3	0.5	0.7	4.39%
Throughput rate (C_{31})	0.0941	0.2	0.6	0.6	0.6	7.89%
Cycle ratio (C_{32})	0.0592	0.2	0.5	0.6	0.8	4.94%
Delivery efficiency (C_{33})	0.0424	0.1	0.2	0.5	0.5	0.96%

As shown in Table 5.9, the final weights are acquired according to the five-dimensional implementation methodology as expressed in equation (44). The final integrated and normalized weights indicate that the events related to worker and equipment operating conditions are the very key elements and should be focused most so as to improve the value-added process efficiently, as their weights are the higher ones.

6. Conclusions and Further research

The fuzzy five-dimensional KPIs implementation model established in this thesis is constructed by complex event progressing, analytical hierarchical processing, key performance indicator analyzing and fuzzy sets through learning relevant material and resources, setting up a system integrating events and critical KPIs. This model helps to adjust the focus on operations in a discrete manufacturing plant, so as to put the limited sources on the most efficient part which contributing to the value-added process. In other words, execute better the 20/80 rules. At the beginning, complex event progressing is applied to analyze critical success factors that have large influence on the overall performance of a manufacturing plant, after which a hierarchal structure is established. Then the five dimensions, significance, frequency, predictability, observability and time sensitivity, are considered as well as characterized as mathematic expressions to obtain the weight of complex events. The results are obtained by means of fuzzy theory and analytical hierarchical process. Especially, the first dimension, significance is combined directly to the importance of related KPIs, while the other four dimensions are converted from events analyzing. After obtaining the five evaluation parameters, the final weight of each KPI can be determined, then the events or elements with largest weights are supposed to be paid more attention to, that is to say, their priorities are high. In the case study, worker efficiency, OEE index and first pass yield are proved to be the most critical KPIs by implementing the five-dimensional model and actions could be taken to around these elements or event to optimize value-added process.

Although this brief study may have a reference value on the performance evaluation system improvement to some extent, there are several aspects that are not dealt with well. Future research can continue from the following aspects. First, this thesis considers only five properties of complex events, actually the real situation could be quite different. This could be improved by analyzing with a more considerable and reasonable methodology. What's more, the mutual relationship among KPIs are not handled, so do the mutual relationship among complex events. Besides, the model needs to be updated dynamically according to real situation, since human subjectivity has limitations and can be amended by experiences accumulation.

To conclude, the implementation of KPIs will always be a subject worth studying and researching.

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Appendix

Questionnaires examples for S, F, P, O, T

Questionnaire for plant intrinsic KPIs significance pairwise comparison
This questionnaire is designed to help improve plant manufacturing process, please choose the most suitable one according to your knowledge and experience. *Thanks for your patience and collaboration.*
Please fill in the former ☐ with the following instructions: 1 if you think the left-side element is equally important with the top-side element; 3 if you think the left-side element is weakly important than the top-side element; 5 if you think the left-side element is fairly important than the top-side element; 7 if you think the left-side element is strongly important than the top-side element; 9 if you think the left-side element is extremely important than the top-side element; 2, 4, 6, 8 for the intermediate importance between the 2 adjacent values. **Please fill in the latter ☐ with the following instructions:** Choose number 0.1, 0.3, 0.5, 0.7, 0.9 to represent your attitude. For example, 0.1 for extremely positive attitude, 0.5 for neutral attitude and 0.9 for extremely negative attitude.

First part:

Cost-related KPIs	Worker efficiency		Asset depreciation rate		Energy consumption level		Inventory carrying ratio		OEE index	
Worker efficiency	1	0.5								
Asset depreciation rate			1	0.5						
Energy consumption level					1	0.5				
Inventory carrying ratio							1	0.5		
OEE index									1	0.5

Second part:

Quality-related KPIs	Quality ratio		First pass yield		Rework ratio	
Quality ratio	1	0.5				
First pass yield			1	0.5		
Rework ratio					1	0.5

Third part:						
Quality-related KPIs	Quality ratio		First pass yield		Rework ratio	
Quality ratio	1	0.5				
First pass yield			1	0.5		
Rework ratio					1	0.5

Questionnaire for plant intrinsic KPIs frequency pairwise comparison					
This questionnaire is designed to help improve plant manufacturing process, 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 frequency expression that you think describes best the occurrence rate with respect to the specific event.					
Event 1: worker absence					
Occurrence rate / Frequency	$\geq 1 \frac{time}{day}$	$\left[1\frac{time}{week}, 1\frac{time}{day}\right]$	$\left[1\frac{time}{month}, 1\frac{time}{week}\right]$	$\left[1\frac{time}{year}, 1\frac{time}{month}\right]$	$\leq 1\frac{time}{year}$
Extremely high					
Intermediate between 2 scales					
High					
Intermediate between 2 scales					
General					
Intermediate between 2 scales					
Low					
Intermediate between 2 scales					
Extremely low					
Event 2: equipment purchase					
……..					

Questionnaire for plant intrinsic KPIs predictability pairwise comparison					
This questionnaire is designed to help improve plant manufacturing process, 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 predictability expression that you think describes best the time interval between incident occurrence and awareness.					
Event 1: worker absence					
Time interval / Predictability	$real\ time$	$within\ 10\ min$	$[10\ min, 1\ hour]$	$[1\ hour, 1\ day]$	$\geq 1\ day$
Extremely easy					
Intermediate between 2 scales					
Easy					
Intermediate between 2 scales					
General					
Intermediate between 2 scales					
Difficult					
Intermediate between 2 scales					
Extremely difficult					
Event 2: equipment purchase					
……..					

Questionnaire for plant intrinsic KPIs observability pairwise comparison

This questionnaire is designed to help improve plant manufacturing process, 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 predictability expression that you think describes best the time interval between incident occurrence and handling.

Event 1: worker absence

Time interval / Observability	$real\ time$	$within\ 10\ min$	$[10\ min, 1\ hour]$	$[1\ hour, 1\ day]$	$\geq 1\ day$
Extremely easy					
Intermediate between 2 scales					
Easy					
Intermediate between 2 scales					
General					
Intermediate between 2 scales					
Difficult					
Intermediate between 2 scales					
Extremely difficult					

Event 2: equipment purchase

……..

Questionnaire for plant intrinsic KPIs time sensitivity pairwise comparison

This questionnaire is designed to help improve plant manufacturing process, 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 predictability expression that you think describes best the severity of time delay between event occurrence and handling.

Event 1: worker absence

Time sensitivity \ Severity	Ignorable effect	Small loss	Intermediate loss	Large loss	Great loss
Extremely high					
Intermediate between 2 scales					
High					
Intermediate between 2 scales					
General					
Intermediate between 2 scales					
Low					
Intermediate between 2 scales					
Extremely low					

Event 2: equipment purchase

……..