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A method for the acquisition of users requirements in discrete manufacturing cell systems

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An appropriate specification of user requirements is considered as an essential step leading to the successful implementation of manufacturing cell control systems. It is predicted that the number of Discrete Cell Control (DCC) systems is likely to show a significant increase in the near future. This demand calls for methods to establish a thorough understanding of user needs. These methods, if applied appropriately, could be used for the acquisition, synchronisation, analysis and specification of user requirements. This paper reports a method specifically developed to assist the acquisition of user requirements on DCC systems. End-user companies are usually unwilling to invest capital and time at the beginning of a project, therefore, to try to overcome this hurdle, a Short-Period Modelling Method (SPMM) has been created. The method bridges the gap between the existing formal modelling methods and the practical needs of industry. The method is simple to learn and easy to use, but it takes multiple views into account so that the resultant models provide a relatively complete picture of the system under consideration. It has been developed for use during the initial stages of DCC evaluation, as indicated by a research project using the combined expertise and experience of a consortium of academic, vendor and industrial user interests.

Keywords: manufacturing cell systems, requirements analysis, modelling methodology

Introduction

There is a need, in the current industrial and economic climate, for well planned strategies and systems to support the infra-structure of manufacturing operations[1], but progress is being restricted by the void between the operational requirements of the upper Management Information Systems (MIS) and the lower levels of shop floor control. The Discrete Cell Controller (DCC) is considered to be capable of satisfying this role within a manufacturing cell.

A manufacturing cell is a group of manufacturing resources, consisting of machines and workstations which are organised and scheduled as an entity to accept discrete parts, sub-assemblies and materials. The cell adds value through processing to create a new identifiable product as its output. Cells may be automated, semi-automated, manually operated or a mixture of all three types. The Discrete Cell Controller provides a manual and/or automated service to accept orders for work into the manufacturing cell and optimises the resources and materials required to produce the finished products. It also provides a monitoring and reporting capability on the progress of requested work and the status of the manufacturing resources within the cell. It is, therefore, essential that the DCC is designed to cope with the diverse needs of the manufacturing community.

Requirements acquisition and capturing establish an understanding of the users need. The importance of acquiring proper users requirements has been

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emphasised by a number of authors[2–5]. However, a good system requirement specification has never been easy to realise. Requirement errors are often not uncovered, until the integration and acceptance tests are complete. In some cases, this may not be apparent until after the system deployment. Studies have revealed that the cost of correcting errors at the early requirements development stage could be one-tenth to one-thousandth the cost of resolving them during or after the final test. Indeed, one primary risk of introducing a DCC is related to inadequate requirement analysis[6]. It is argued that this can be minimised by the use of a formal modelling method to analyse the users' manufacturing requirement problems and precisely define their requirement. There are however considerable penalties in employing structured development methods, such as: long completion time, complex notation, high cost, and voluminous documents, as listed by Billo et al.[2]. These are meaningless to the average users, as pointed out by Harke[7]. Less formal and simple communications with shop floor personnel is a basic requirement in acquiring user requirements for introducing a DCC into a discrete manufacturing cell system[8]. To address this, a preliminary modelling phase is necessary to efficiently capture the users requirement and analyse the data. The Short Period Modelling Method (SPMM) was created to satisfy this need.

The SPMM method, though easy to use, seeks to create an overall picture of a cell system. This is achieved by modelling a cell system from multiple views, namely: *concept, activity, information* and *dynamic*. The method defines the boundary of the system to be studied in the conceptual model, illustrates the activities necessary to perform the functions of the system in the activity model, depicts the data structure of the system in the information models, and models the system behaviour over time in the dynamic model.

The SPMM is geared to the acquisition of users requirements at the initial stage of a project and it plays a unique role in an integrated modelling method for the cell control system. A brief account of this parent method will be introduced in the next section of the paper in order that a global perspective of the modelling method at the Cell level is provided. One of the three principal constituents of this parent method, *Capture and analyse users' requirements*, is further discussed in a separate section, in which the importance and difficulties of users active participation are reviewed, and solutions for these difficulties are suggested. The SPMM method is then elaborated in each of the individual viewpoints, and the conclusions are stated in the final section.

The Integrated Cell Control Modelling Method (ICCMM)

The Cell level, which interfaces between the Section/Area level and the Station level in a CIM hierarchical model, is complex and no existing modelling method has the capability to model the entire life-cycle of a cell system implementation. To achieve this, a modelling method would have to address issues such as the performance characteristics, application functions, real-time control, and off-line/on-line databases. On the other hand, most of the individual components and activities have been addressed separately in different methods, and an integration strategy for cell system modelling is a feasible 'best scenario' for the near future[9]. Attempts have been made towards applying an integration strategy to solve the complicated modelling problem in CIM studies, but they have been insufficient to fit the modelling requirement at the Cell level. Support for this assertion has been reasoned previously by the authors[10]. The Integrated Cell Control Modelling Method (ICCMM) is therefore proposed to satisfy these current deficiencies.

The ICCMM is intended to optimise the power of existing methods and techniques to deal with the different perspectives of the modelling process and to develop other methods to rectify any deficiencies. The main stages of the ICCMM method are shown in *Figure 1*, namely:

1. Capture and analyse users' requirements on a manufacturing cell system
2. Construct models for the cell control system
3. Verify the cell control system models.

The first activity is dominant because it forms the basis for further investigation into a specified system. Its output *Users' requirements description* presents users requirements in their familiar format so that they can easily check whether their requirements are fully taken into account; whilst, output *requirements models* represents the users requirements in a designed framework and serves as an input for the other two activities. Another output *suggestions for cell control system* varies according to the analysis results. For example, a computer-based cell controller is expected to improve the system control, but it is not always necessary to add a computer as the cell controller into the system.

The second activity is concerned with constructing cell control systems to meet the users' requirements, which were identified in the first activity. It takes the *Users' requirements models* as its input and produces *A complete cell control system model*. If the users' requirements are recognised to be too difficult to realise, then *Suggestions for compromise* will be put forward. This activity also provides a *Functional model description* which explains the functions to be possessed by the cell control system.

The last activity assesses whether the resulting cell control system model meets the users' requirements, and whether the implementation of the cell control system is feasible. If there is a problem, it makes adjustment suggestions which will be fed back to the relevant preceding activity boxes. If there are no

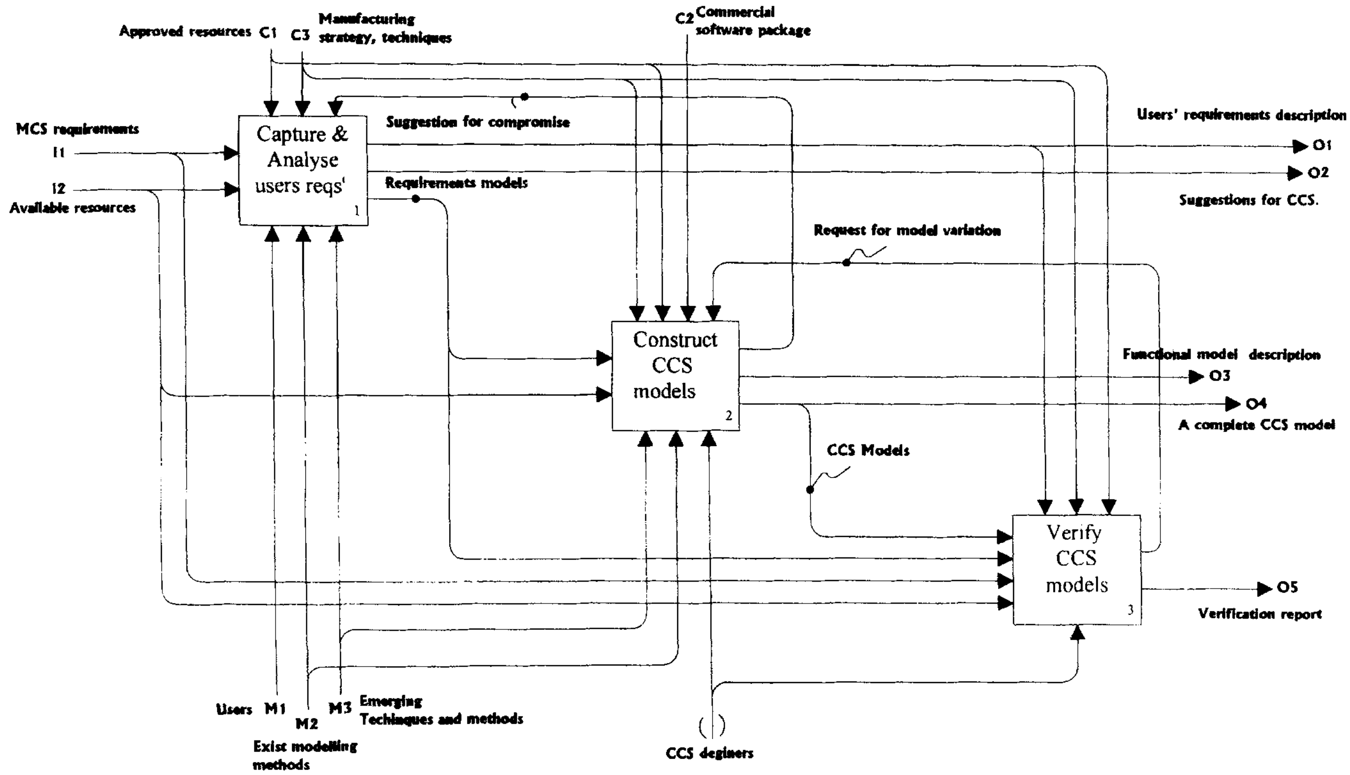

Figure 1 Simplified A0 diagram of ICCMM.

problems, the modelling process is finished when it reaches the end of this activity. This activity generates a report which contains the verification results.

Capture and analyse users' requirements

This is the first task in the development of ICCMM. Indeed, it is important to ensure that users' major requirements are adequately captured, well understood, carefully analysed, and properly represented, so that the model resulting from this stage, forms an appropriate foundation on which the system may be further studied, ranging from system design, analysis, through to implementation.

Users participation

It is crucial for users to be involved in the initial modelling phase, because users' active participation could ensure that their original requirements are correctly stated at the beginning of a project, and subsequently are satisfied through design and implementation to get their desired system. Otherwise, they may have to confront difficult situations, either to accommodate a system which has drifted away from their original desires and needs, or to spend a large amount of money and effort to modify the resultant system.

However, difficulties do exist in managing users' participation. Substantial problems are associated with the expression of their requirements and communicating them to system modellers. System modellers find it difficult to translate verbally expressed user's wants into a formal specification. This process is not helped by the standard notations used in formal modelling methods, because they are meaningless to average users. Existing formal modelling methods normally have a large number of specific terms, conventions, and rules. They are difficult to comprehend and are not readily acceptable by un-informed shop floor personnel, who may prefer to use their own familiar terms and language to represent the system under consideration. Likewise, the system modeller could also be confused by these personal conventions, because they are more used to the representations of formal methods. There is obviously a big gap between the preferences of the end users and the system modellers. Although users can be trained to use the formal methods to overcome this problem, it is arguable that this could result in a loss of contact with the original user perspective.

A feasible solution is therefore required which can improve the communication between users and system modellers and facilitate the users' active participation in the modelling process.

Two phases of the modelling process

The proposed solution to the aforementioned problems is to divide the whole modelling process into two phases, namely the *preliminary modelling phase* and the *formal detailed modelling phase*. The general concept of this strategy, in which the first phase is an additional phase to the traditional modelling process, is shown in *Figure 2*. The main objectives of this preliminary modelling phase are to:

1. improve the communication between users and modellers,
2. capture and clarify users' requirements, and reduce users' uncertainty,
3. facilitate agreements between the users and system modellers on the requirements specification. and between different users, e.g. from different departments,
4. ensure the effective validation of the modellers' view of the system by the users,
5. create models upon which further modelling could be conducted to generate improved systems.

After completing the preliminary modelling phase, a decision is made whether further modelling is necessary. If not, the resulting models can be used to provide a discussion platform to review the current system in order to suggest improvements. If further detailed modelling is required, the resulting models together with the information gathered in the preliminary phase can be used as a start point.

The purpose of adding the preliminary modelling phase is to merge the formal modelling methods with the practical needs of the user. Therefore, the preliminary modelling phase should be close to the shop-floor personnel conceptualisation of the problem domain. Meanwhile, efforts should be made so that the modelling results of this phase are ready for transferring in the later study. In this way, a possible trend of 'drifting' away from users original desires can be avoided as the modelling process moves forward.

The Short-Period Modelling Method

A Short-Period Modelling Method (SPMM) was developed to facilitate the modelling process in the preliminary phase. A cell-tailored modelling framework was built in the SPMM, which provides a foundation for the integration of models developed in different views and can be used as a guideline in the modelling process. Underlying the framework, tables are created to assist users' requirements gathering, and to make sure that the necessary information is acquired. The method develops new concepts and integrates the ideas from known modelling methods. It aims to provide an easy to use method, simplified but complete, which would cover the multiple important views of a manufacturing cell system.

Integration

An *Integration* capability within the SPMM combines several existing methods to tackle the cell system

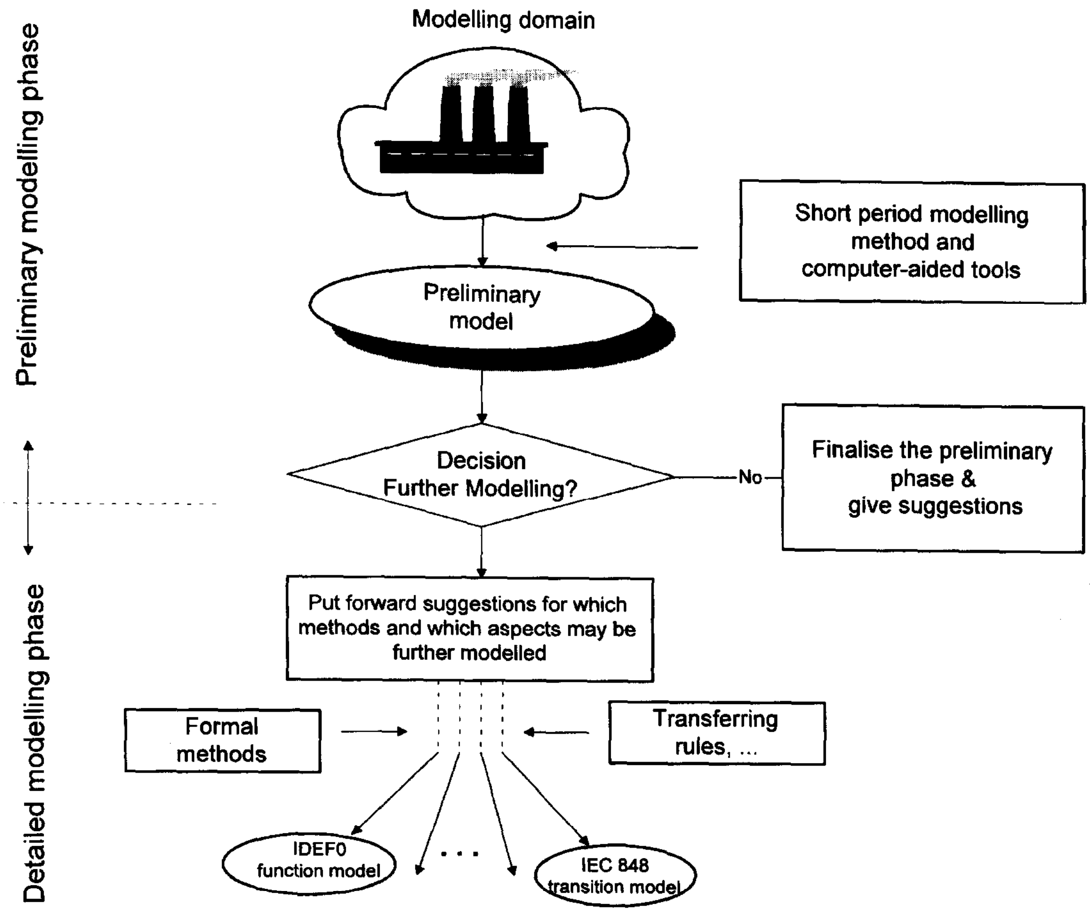

Figure 2 Two phases of modelling strategy.

modelling problem. For example, it takes the ideas of structured analysis of systems to develop hierarchical models of a complex system. It also borrows the idea of a context diagram that presents the relationships between a system and its environment. This is considered to be preferable to applying different methods to unrelated aspects of the system or to disjointed phases of the system life cycle. In this way, the SPMM can not only combine the advantages of several methods, but also avoid the difficulties in transferring models produced by different methods because each formal method has its own syntax and semantics. It is also difficult and time consuming for end-users to become competent in all the component methods. Furthermore, it is almost impossible for a small or medium-sized manufacturing company to possess or license a number of modelling software packages.

Multiple modelling views

A viewpoint can only represent a system with emphasis on limited concerns. Multiple-views are therefore needed to present a global picture of a system. Currently, there are no available international standards for modelling views at the Cell level in manufacturing systems. Considering the objectives of the preliminary modelling phase, the four views defined in the Framework for Modelling prepared by the European Standards Institution as a pre-standard in the CIM research domain[11], offers a convenient foundation. The SPMM models a cell system from four different views, namely: Conceptual, Activity, Information, and Dynamic. The consensus is that the important aspects of cell systems could be described by these four related, but different, views. The conceptual view model addresses the working scope and working objectives of the modelling process, including the users' business requirements, if deemed necessary. The activity view model is concerned with what activities a system has to perform to implement the functionality of the system. The information view model considers what data the activities are related to. Finally, the dynamic view model focuses on the control aspect and temporal behaviour of the system.

The conceptual view modelling aims to present an approximate picture of the system being studied. This could be in any system modellers' preferred format and, therefore, does not require further specific discussion. Although the authors believe that the four related views are required to provide an overview of the system being studied, a particular application may choose either, or all of them, in the preliminary modelling phase.

Activity view modelling

The Activity view is concerned with what activities a system has to perform to achieve its desired goals. It models the system from the transformation point of view and concentrates on inputs and outputs of, the system and the activities, in the system. Principal objectives of the Activity view modelling are:

1. to provide a general description of the system being studied, by defining the main activities and the flows between these activities,
2. to define relationships between the cell system and its environment by defining the related external activities/flows and the flows between the cell activities and these external activities/flows, and
3. to provide a foundation for Information and Dynamic modelling.

Activity category

An Activity is a process which causes changes in inputs. A major activity may be decomposed into sub-activities which can be further decomposed. A system has to perform a series of activities to realise its functionality. In a manufacturing cell system, an activity may be grouped into one of the following four types: Transform, Transport, Inspect, and Storage[12]. The type 'Others' is added to the activity-type in the SPMM in order to accommodate those not belonging to the four defined types.

Transform: describes the act of change of the attributes of its activity objects from one form to another, e.g. a simple machining activity changes the physical appearance of raw material, and a despatch activity transfers the received schedule plan into a work-to-order list for a particular machine.

Transport: describes the act of moving activity objects from one point in a cell to another point.

Inspect: describes the act of assessing the compliance of all inputs to determine their conformance to a specification.

Storage: describes the act of retaining the inputs at a specified location until they are required to be transported.

Others: describes activities not belonging to the above defined four types.

Modelling methodology

Boxes are used to represent activities and arrows are used to represent flows. Each activity may be decomposed into more detailed sub-activities at a lower level. The basic symbols used in Activity view modelling are:

1. The rectangle represents an activity (round-corner rectangle represents an external entity).
2. Heavy black lines represent flow of material.
3. Dotted lines represent flow of information.
4. Solid lines represent flow of control.

This SPMM element is similar to the basic element of $IDEF_0$. However, changes are made to simplify the modelling process and to enhance the presentation quality. These changes are mainly reflected in the following three aspects:

1. decreasing the number of flow (arrow) types around one activity box,
2. adding external entity boxes to the activity model,
3. assigning attributes to flows and distinguishing them by the combination of colour coding and line type.

Flows (arrows), in the SPMM, form the messaging system of a cell. It describes relationships between cell activities, and between a cell and its environment. Flows are grouped into two types: *input* and *output*. Whilst the flows (arrows), in $IDEF_0$, are classified into four types, namely, *input, output, control* and *mechanism*. *Control* flow in $IDEF_0$ is aggregated into *input* flow in SPMM. This can significantly ease the modelling processes, especially at the initial stage of the requirements analysis phase, because it is sometimes difficult to distinguish the *input* from *control*. *Mechanisms* (resources) in $IDEF_0$ are not considered in SPMM for the consideration of brevity. The authors believe that this will not substantially diminish the completeness of the model, because, in a cell system, *mechanisms* (resources) are usually clear to the end-users or system modellers, even though they are not indicated on the activity model. Furthermore, mechanisms (resources) of an activity will be considered in Information modelling. The addition of external entities on the activity view diagram provides a view on the relationships between the cell and its environment on the top-level model, and clarifies the system boundary.

In a manufacturing cell system, Flows transferring between the activities, are classified into one of three attributes: *information, control*, and *material*. The *information flow* consists of instruction information and response information. Instruction information usually comes from a higher level to a lower level, which gives instructions on how the activity is to be performed, e.g. CNC coding. Response information usually moves in the opposite direction to the instruction information. It reflects the performance of the activity, as well as the state of the resources or material involved in the execution of the activity. The *control flow* initiates, alters or terminates an activity and comes either from a higher level, the cell controller, or from operators. The *material flow* includes all the physical matter related to the product during manufacturing, namely raw material, parts and assemblies, product and scrap material. The assigning of attributes to flows and distinguishing them by a combination of colour coding and variety of line type in the SPMM diagram enhances the readability and clarity of the model. When the use of different colour is not possible, e.g. hard copy material, the line type itself is sufficient to indicate the differences.

Analysis of activity view modelling of cell systems

After the Activity view model of a cell system has been obtained, the analysis process is conducted. It aims to discover problems in the current system and to suggest possible improvements in system performance. The process of analysis consists of three steps:

Step 1. To analyse the established Activity view model of a cell system.

(This step is only relevant for an as-is system; for a to-be system, start from Step 2).

Step 2. To propose a new or improved activity model of the system which can either solve perceived problems or provide better descriptions of the system being studied.

Step 3. To indicate the support required in order to implement the proposals which might be put forward in *Step 2* and to suggest potential improvements which might be brought about through the implementation of the proposals.

Step 1. To analyse the established Activity view model of a cell system

This step is mainly concerned with the clarity and presentability of the resulting Activity view model. If it is found that the resulting model is not sufficiently clear in presenting the system, the activity models should be revisited. It may be advisable, either to split the cell into two or more, if the cell is too large and is functionally splittable. Otherwise, models can be simplified by neglecting non-essential activities if the cell is not splittable. An alternative is to establish multiple levels of the Activity view model. If only a part of the model is not sufficiently clear, we need to consider whether that part can be decomposed, or whether the burden of the activities in the cell are not balanced. In the latter case, the workload of the activities may be re-arranged to alleviate the problems of work overload in some of the activities.

Step 2: To propose a new or improved activity model of the system which can either solve perceived problems or provide better descriptions of the system being studied.

This step can be further decomposed into two sub-steps:

Step 2.1. To analyse any perceived problems and to make suggestions on what adjustments should be made.

Most of problems perceived in a cell system can be categorised into areas covered by application functions, e.g. Quality Control, as defined by Franks et al.[13]. These application functions cater for various requirements, which vary greatly for different users and different companies. It should be helpful to develop a set of questions against each of these application functions and provide appropriate answers. In the case of Quality Control, a focus is put on the monitoring, control and traceability of quality problems. Questions and consideration of each question might be given as follows:

Question 1. Is the quality of brought-in goods monitored? It is considered advisable *to monitor brought-in goods.* If brought-in goods are not monitored, it will be difficult to trace the causes of quality problems if they are detected at a later stage. Furthermore, if problems in brought-in goods can be discovered earlier, they can be reported and solved in time. If information regarding the quality of brought-in goods is not available, inspection should be applied and the quality level of the brought-in goods should be created, recorded and stored.

Question 2. Is quality control carried out on the finished product or at each manufacturing activity? and *Question 3. Who is responsible for quality (is an inspector used or do operators act as inspectors)?* If the quality requirement is high, or the process period is relatively long, it may be desirable *to carry out quality control procedures at each manufacturing activity instead of on the finished product.* In this circumstance, it would be more suitable for operators, not inspectors, to carry out the inspection task for considerations of economy and efficiency. However, if the inspection needs special skills, further considerations may be taken into account, e.g. cost of training operators.

Question 4. Do the outgoing goods carry inspection information? It may be advisable *to attach quality information* to the outgoing goods so that the same inspection work will not be repeated in the succeeding process.

Responses to such questions about the current situation can be used to re-shape the initial cell system configuration. The same approach can be applied to other application functions. In a case where some requirements can not be categorised into defined application functions, a problem-specific solution may be taken. For example, users may be interested to know whether adding a new activity in the cell is beneficial. A feasible method would be to add the new activity to the existing system activity model and to restart the analysis process from *Step 1.* Other problems may need more information before their solutions can be determined. In such circumstances, the problems may be deferred until after the modelling of the Information and Dynamic views.

Step 2.2. To analyse whether the resulting activity model is appropriate irrespective of whether perceived problems do exist.

It is not unusual for users not to realise the problems that exist in their system simply because of familiarity. Defining the criterion for an 'appropriate' activity model is often the most difficult aspect. One approach is to examine whether the system being studied conforms to certain commonly accepted rules and concepts about a cell system. For example, a cell system should have a clear boundary and the flows of material and information across the boundary should be minimal[1]. The cell control system should also be capable of making full use of all kinds of resources within a cell to fulfil the assigned tasks through efficient management, co-ordination and control. To this end, it is essential to identify a clear boundary for the system and to identify a control structure to achieve efficient control. The division of tasks (activities) should be rationalised in order to make full use of resources and to avoid any bottle-neck problems. As to individual activities in the cell system, each of them should have appropriate inputs (instruction and parts) to complete its task. The performance of activities should be monitored, because the cell on-line states are essential for the control system to realise efficient co-ordination within the cell. Based on these arguments, the following questions arise in respect of analysing the Activity view model of a cell system:

1. If the system has a clear boundary, what are the information and material flows across it? Can the number of these flows be reduced?
2. What is the control structure of the cell system? How many control authorities does it have? If more than one control authority exists, what are their relationships (priority) with other authorities?
3. Is the work burden of the principal activities rational?
4. Does every activity have an appropriate input to enable it to complete its tasks? Is the performance of activities monitored?

Suggestions for improvements should be proposed according to the results of the analysis (i.e. answers to the above questions).

Step 3. To point out support required in order to implement the proposals which might be put forward in Step 2 and to suggest potential improvements which might be brought about through the implementation of the proposals.

This depends upon the analysis results from Step 1 and Step 2. The support could include a 'software' side and a 'hardware' side. The 'software' side should contain, for example, the commitment from shop floor personnel. The 'hardware' side may require new investments, e.g. device installation. Examples of potential improvements include the enhancement of product quality and the alleviation of bottle-neck problems.

Information view modelling

In the domain of the information modelling for computerised manufacturing, research projects have been carried out from various perspectives. For example, Hsu and Rapttner emphasised the *information integration* in the facility in their paper[14]. Sanoff and Poilevey, on the other hand, focused on the *information processing* aspects of the CIM subsystems that schedule and control a workshop[15]. The acquisition of knowledge relevant to the information system, for a discrete manufacturing cell system in particular, remains to be addressed.

Information view modelling in SPMM emphasises information capturing. This is different to conventional information modelling methods, e.g. IDEF$_{1x}$, SSADM which usually aim to produce entity-relationship-like models of the system being studied. The SPMM aims to help users establish the basic concepts of information view modelling, the resultant model forming an information facet of the preliminary model of the cell systems and providing fundamental data (requirements) needed in the final information model of a cell system.

Important aspects of cell information modelling

An information system is a system that collects, stores, retrieves, processes and displays information[16], of which *Collection, Storing*, and *Display* are more relevant at the requirements capture and analysis stage. *Retrieve* and *Process* have been left for consideration at a later stage in the system development since they are related to information processing and requirements on them can be deduced from others. In addition, the actual information stored in a cell information system is also important and the term *Data components* is used instead of *Information* in order to avoid confusion. Four aspects of the cell information system are concerned with are listed below:

1. Data components—what data are stored or should be collected in a cell system.
2. Acquisition (Collection)—how and when data enters into the information system
3. Storing—how and where the data are stored
4. Display—what content, in which format, by what mediums, and to whom the data in the information system should be presented.

Data components: this aspect is concerned with what data should be collected and stored in an information system, so that the information system can provide the right information to the right place at right time. It is better to exclude non-essential data components so that the management of the cell information system (which could utilise a database if a computer system is used) does not become too complex. Four types of data, namely *Activity*, *WIP*, *Facility*, and *Personnel* have been defined as basic data components in a cell system, but detailed information about these may vary in different systems. The essential elements of Data components of the *Activity* type are listed in *Table 1*. This list does not include all the necessary elements, as it merely serves as a guideline in the modelling and analysis stages. Clearly, interrelationships exist within four types of data: *Activity* needs *Facility* and *Operator* to complete its process; and *WIP* will be processed by a sequence of *Activities*. These interrelationships should also be reflected in the corresponding Data-components.

Acquisition: this is concerned with how and when to obtain the required information (data components). The data can either be down-loaded from the higher level, or be collected from within the cell system. The particular approach usually depends on the nature of the data to be acquired, which can be classified as static or dynamic. Static data do not change with time and usually consist of the cell constituents (e.g. the features of a machining centre, machine types in the cell etc.). This type of data component is more likely to be down-loaded from the higher level of the information system or pre-set at the initialisation stage. Dynamic data changes with time (e.g. the operation time of a machine) and, therefore, is more likely to be collected automatically or manually during production. A cell system may adopt either or both of the two acquisition approaches. Whether the data should be collected on-line or off-line is also closely related to the nature of data acquired and the control mechanism used in a system. Static data can be obtained off-line, while dynamic data should, ideally, be collected on-line and therefore, the time interval of sampling should be considered.

Storing is concerned with where and how data are stored. If a cell has an information store in the system, it should be considered whether data elements should be resident in the cell or sent to an information system at a higher level. Whether data

Table 1 Data components Definition—1: Activity

{	
Static:	
Identifier:	{id, name, type...};
Description:	{function...};
Rqtseq. description:	{resources required (operator numbers, capacity*...) (machine number, capacity...)};
Others:	{user specific description};
*To indicate inter-relationship between Activity, Facility, and Personnel.	
Dynamic:	
State:	{wait, in-process, completed, failed, suspended...};
Variables:	{period for completion...};
Abnormal events:	{cause record, action taken: what action and taken by whom...};
Others:	{user specific description};
};	

are stored on paper or in some kind of electronic means depends upon the storage system used in the cell, e.g. a document file stored in cabinets or a computer database. Clearly, the storing method of Data components affects their accessibility and retrieving process.

Display is concerned with specifications of the information display medium, format, and other similar issues. The specification is related to whom the information is displayed and this aspect is likely to be of considerable interest to the end-users. It is also of importance to the cell information system, because the specifications for the other three aspects will largely depend on this specification. For example, if information is required to be displayed on a screen (e.g. a computer monitor) in real time, the displayed information should be stored on a computer disk, rather than on paper.

Modelling methodology

A primary task for Information view modelling in the SPMM is to acquire requirements (knowledge) on the information of a cell system, in terms of the four important aspects discussed previously. Important attributes for these aspects are depicted in a tree structure, as shown in *Figure 3*. Complementary tables have been created, on the basis of the tree structure, to facilitate the modelling process by guiding interviews and assisting the information capture. Each table indicates detailed information particularly required for one aspect. In other words, one aspect has a corresponding type of table, which in turn may have several variations. For example, *Data Components* has four tables, catering for four different types of *Data Components*. An example is illustrated in *Table 2*. Special considerations have been given to the design of these tables:

1. To assist the recording of information during the interviews, a reference index system is adopted in these tables. It is not easy to predict how much information could be acquired from an interview for a particular 'cell' in the tables. Therefore, each 'cell' in the tables is marked with a unique reference index. In this way, corresponding information can be recorded somewhere else without space constraints. One reference index normally uses two capital letters to indicate which table it belongs to, and two digital figures show its position in the table (the top row and the leftmost column is sequenced as '0'). It could have one small letter at the end which would show if it belongs to the existing system or to a new proposal: 'e' for existing system and 'n' for new proposals. In information modelling, the first two letters T and I remain the same. T is an identifier for table and I for information.
2. Every row, except the top one, in these modelling tables is split into two. The first one records the existing information system, and the other caters for new proposals. This arrangement facilitates comparison, which is necessary in conducting the analysis.

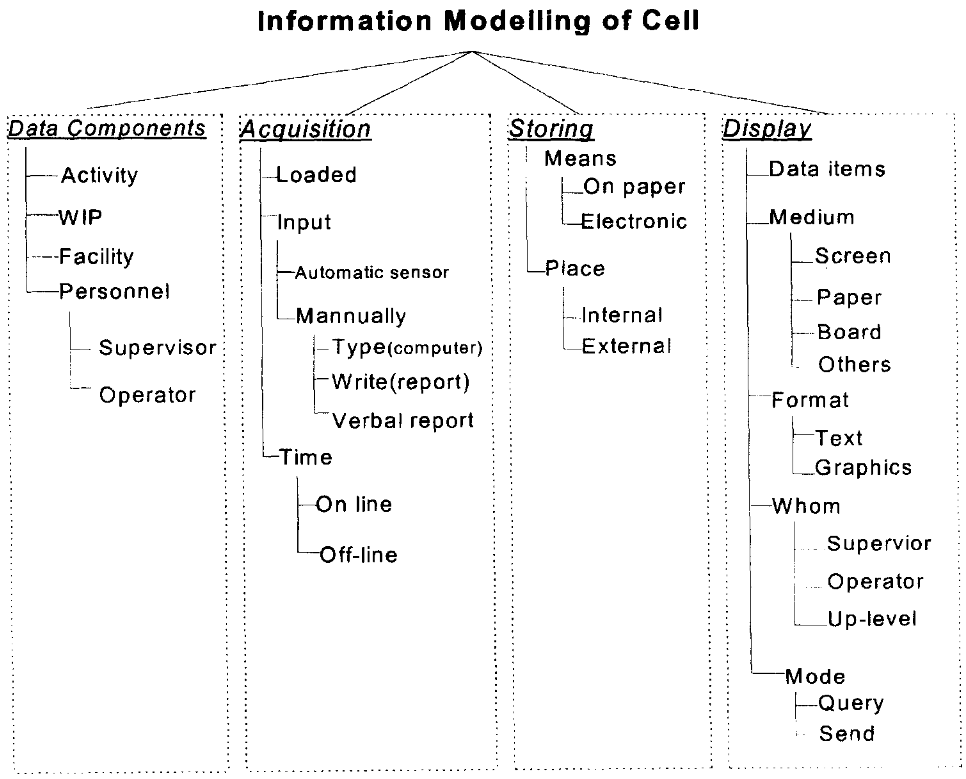

Figure 3 Tree structure of important aspects in information modelling of a cell system.

Table 2 Modelling-and-analysis-table for *Data component*—Activity

	Attributes	Considered attributes
STATIC	General information:	as-is: T.I.(2-1).1.1e
	identification, name, resources,...	to-be: T.I. (2-1).1.1n
	Others:	as-is:
		to-be:
DYNAMIC	State:	as-is:
	wait, in-process, completed, failed, suspended,...	to-be:
	Other variables:	as-is:
	period for completion...	to-be:
	Abnormal events:	as-is:
	report, automatic diagnosis...	to-be:
	Others:	as-is:
		to-be:

The information view modelling of a cell system could be decomposed into an activity-based modelling, as demonstrated in *Figure 4*. That is, the information model is developed on the basis of activity model. A set of tables, with respect to all the key aspects, are created for all, or selected activities. The aggregation of these provides a rich picture of requirements on the information view of a cell system. Guidelines and procedures of analysis of the resulting models and captured information (requirements) are similar to those discussed in Activity view modelling. The information capture, analysis may entail a large amount of work. This can be alleviated by concentrating on core activities or core aspects only, which could, however, create the danger of losing the complete picture of a system. A better solution is to develop a computer-aided supporting tool. A prototype of the tool has been developed and will be introduced later in the paper.

Dynamic view modelling

A literature survey shows that research activities, in dynamic modelling, have been focused on quantitative performance evaluations, e.g. the buffer size and the optimal number in a batch size[17,18]. Petri nets and their derivatives, e.g. Grafecet[19,20] are the principal tools used for dynamic system modelling, in particular, the performance evaluation requirement. Petri net based tools often adopt rigorous methods to build up mathematical models for the system under study. However, complicated situations in cell systems are difficult to describe by rigorous mathematical models. Furthermore, at the requirements capture and analysis stage, it is apparent that analysis is essentially concerned with identifying the true needs on a system, not the structure of the solution[21].

Dynamic view modelling in SPMM focuses on information (requirements) acquisition of system

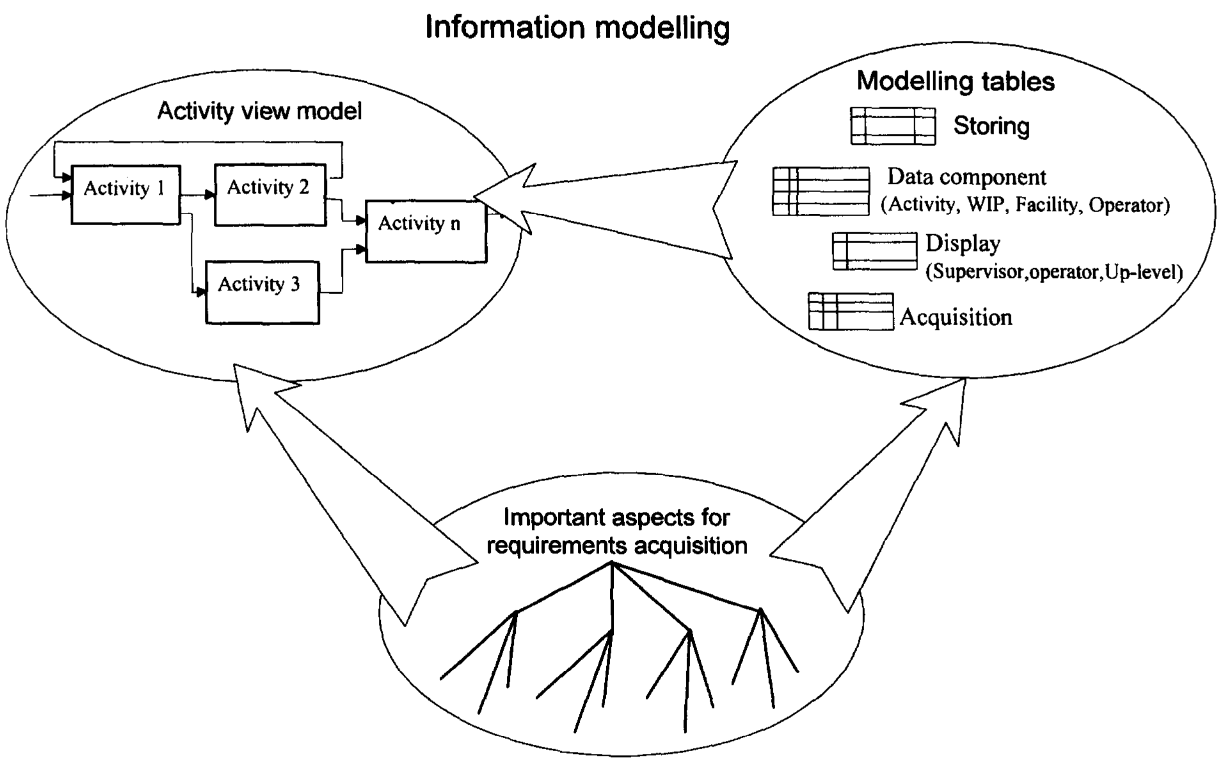

Figure 4 Information view modelling.

behaviour relevant to the dynamic control of a cell system. It is geared to help users build up the basic concepts of a cell system dynamic view so that their understanding, and requirements of the system can be fully captured, and analysed. The resultant models provide the fundamental information required for the final dynamic modelling of a cell system which may be produced by one of the formal dynamic models, such as Petri-nets and IEC 848, in further study.

Important aspects of cell dynamic modelling

The ultimate goal of the study of system dynamics is to achieve the pre-determined control objectives by modelling and controlling its dynamic behaviour. A dynamic model provides the foundation for the design of a control system. Key aspects relevant to the dynamic modelling of a cell system are identified as: *Control objectives*, *Control system*, *Input*, and *Output of the control system*, as shown in *Figure 5*.

Control objectives reflect users' requirements for the modelled systems and indicate goals to be pursued by the control system. Users' control objectives may be vague, especially at the beginning of a project. Therefore, one important task of dynamic modelling at this stage is to help users clarify their control objectives and to clearly represent their requirements for the cell control system, rather than

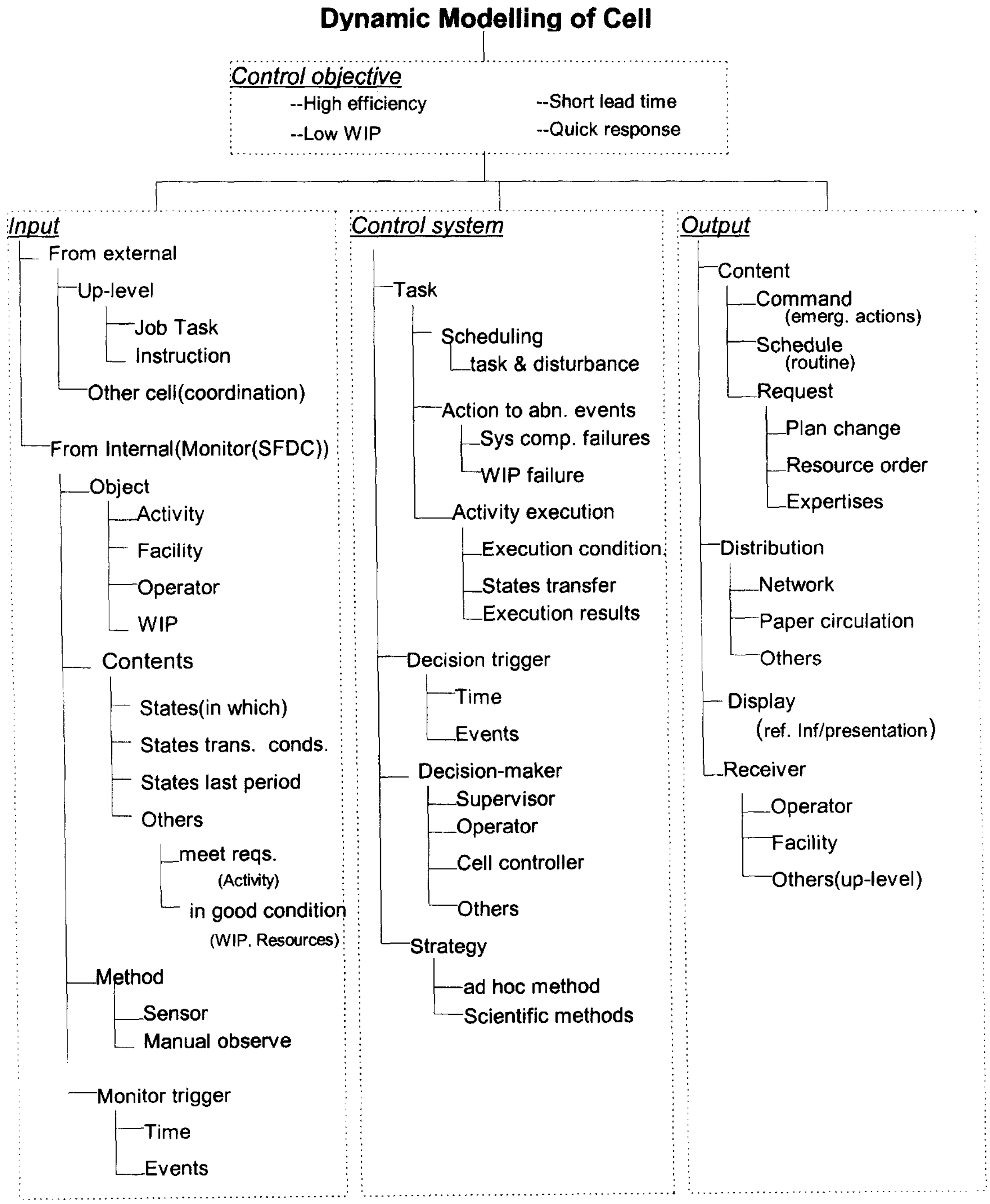

Figure 5 Tree structure of important aspects in dynamic modelling of a cell system.

a detailed specification of the control system. Control objectives could be, for example, high throughput, low WIP, and short lead time.

Control system is designed to achieve the control objectives by accomplishing a number of *control tasks*. It is concerned with:

— what are the control tasks?
— who is responsible for these tasks?
— what causes these tasks to be executed?
— what strategy is used to perform them?

Generally, a control task is bounded by its input and output. The execution of the control task needs a trigger to start its processes and resource to complete the processes following a certain strategy. A general structure for a cell control system and control tasks is shown in *Figure 6*. *Control tasks* of the control system in a manufacturing system can be classified into three categories, namely: *Scheduling, Action to abnormal events,* and *Activity execution*.

The *Scheduling* task is to plan and control production in a cell according to the job tasks received from a higher level. This task is carried out by a supervisor, or a cell controller (computer-based). It may be triggered either by Time or by an Event. A Time trigger means that a scheduling task is activated by a given time interval, or at some particular moment in time. Examples of an Event trigger are: arrival of job tasks (production plans), or any kind of system disturbance, e.g. emergency order, or customers' short notice changes in their order.

The *Action to abnormal events* task deals with unexpected events, including system components failure (e.g. machine out of order, tooling broken, or operator unavailable), or WIP failure (e.g. scrap, or damage caused by transport). The task could be tackled by an operator, supervisor, a cell controller or a specialist.

The *Activity execution* task controls the performance of an activity. It is concerned with the execution conditions, and possibly the internal state transferring of individual activities. For example, the task examines the satisfaction of execution conditions for a machining activity, including: the availability of the machining tool, operator, and the part to be processed. This task is most likely to be carried out by an operator or by a cell controller.

These three tasks will give rise to problems and constantly call for decisions to be made. Whether the decisions are made, on an ad hoc basis or by pre-determined methods, should be specified. However, the purpose of modelling the control system at the short period modelling stage is not to examine how good a particular decision-making strategy is. Therefore, no further detailed discussion will follow on how to select a specific strategy.

Input of a control system can be categorised into External input and Internal input. The former comes from the external system, whereas the latter is generated within the cell system. The *External input* can be further divided into two: one from the higher level and the other from other cells. Input from the higher level usually plays the role of a command, in the form of job-tasks, together with instructions on how to complete the job. Input from other cells could be requests for co-ordination. *Internal inputs* are mainly from monitoring activities (e.g. SFDC-shop-floor data collection). This type of input reflects cell state and

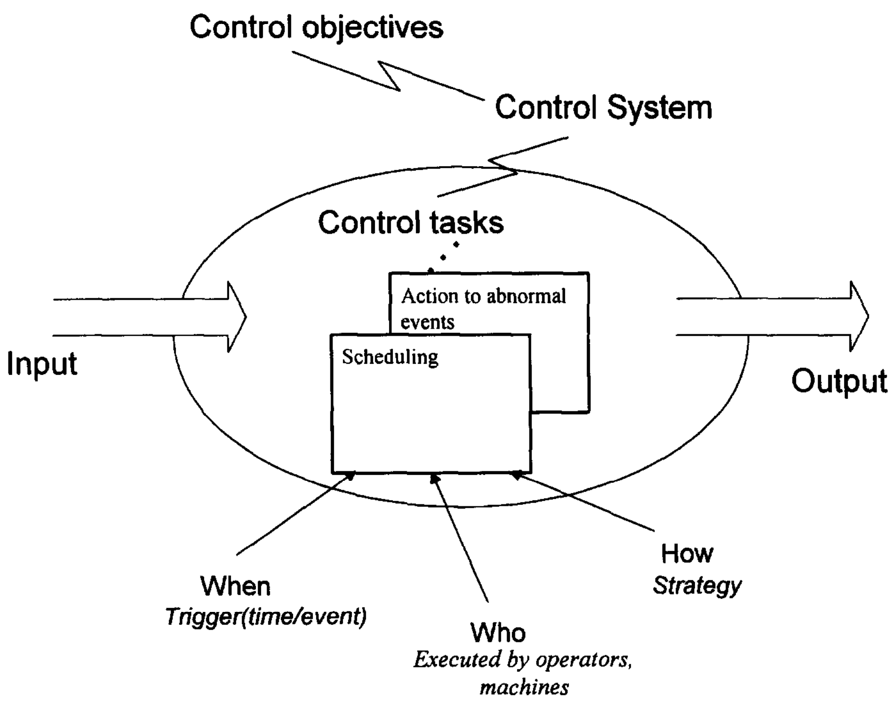

Figure 6 General structure of a control system.

production information, which are essential input for the *Control system* to make appropriate control decisions. Details of the *Internal input* are shown in *Figure 5*. Activity, WIP, Facility and Operator are selected as the objects to be monitored. Their states, conditions of states transference, and the duration of each state, are among the contents of monitoring. These can be gathered either by automatic sensors or manual means, and the monitoring activity could be triggered by Time or an Event.

Output of a control system may be classified into *Command, Schedule,* and *Request*. *Command* and *Schedule* are sent to a Facility and/or Operator in a cell to control the production of parts as specified in the job-tasks. *Command* deals with emergency problems while *Schedule* is for controlling routine production. *Request*, unlike *Command* and *Schedule*, is sent to external systems of the cell. *Request* from a cell control system can be further decomposed into three types: *Plan changes, Resource order* and *Expertise support*. A request for *Plan change* may result from a resource constraint, which may result in the job-task not being completed as required. *Resource order* requests resources which are necessary to complete the production of a particular product. Request for *Expertise support* tackles complicated events occurring within the cell, which cannot be dealt with by the cell system and requires support from an external source of expertise. The manner of distribution of *Command, Schedule,* and *Request* depends largely on the information system used in the cell. Possible distribution means are via a computer network or by the circulation of paper documents. The display of the Output is concerned with problems similar to those discussed in the information system, including display medium and format.

Modelling methodology

To obtain an overall requirement picture of the dynamic control of a cell system, the important aspects discussed in the previous sub-section should be used as a guideline in gathering the special features of a particular cell system under consideration. The information (requirements) acquisition and the modelling method are similar to those discussed in Information view modelling, except for contents of modelling tables different, which are complementary to the tree structure shown in *Figure 5*.

Modelling process and computer-aided modelling tool

In modelling a cell system, it is the authors' opinion that the Activity view should be built first, since it is the most intuitive process. Furthermore, the activity model formulates an overview of a system which can be used as a basis for further modelling. Information on important aspects of Information and Dynamic view modelling are subsequently collected and analysed with the help of tree-structures and their complementary tables. The adoption of a tabular form is not only for facilitating the requirements capture, but also to assure that the full set is captured. The resulting models are then analysed using the similar guidelines to those outlined in the Activity-view modelling.

A prototype computer-aided system modelling tool has been developed to support the modelling process. The modelling tool provides self-explanation window interfaces to ease use. The Activity-Information view model has been developed, on the basis of Activity model, by using the modelling framework provided. The composite of Activity view model and Activity-Information view model forms the basis for Activity-Dynamic view modelling. The temporal attributes are specified for the activities, to form the Activity-Dynamic view model of the system. Transition rule sets and decision-making rules have been added to express the control aspects of the dynamic process. A brief auditing function has also been built in the tool to verify the completeness of the models and to validate whether users' requirements conform to certain pre-set rules and criteria. The information gathered in the modelling process can be inserted into the information and dynamic modelling tables, if necessary, for further study.

Conclusion

The cell level, which interfaces between the Section/Area level and the Station level in a CIM hierarchical model, is complex. This complexity is manifest at the requirements model level, particularly if the purchase of a computer-based DCC system is involved. It is therefore crucial that appropriate methods and techniques are made available to users and vendors to facilitate stepwise derivation from requirement through to implementation. To overcome difficulties often encountered in user requirements capture, the authors recommend the users to divide the requirements capture and analysis stage into two phases: the preliminary modelling phase and the formal detailed modelling phase. In the first phase, the method should be less formal, so that the method can be easily understood by cell users, and no substantial training cost is required. Formal structured methods are then introduced in the second phase to obtain unambiguous representations.

The SPMM has been developed for use in the preliminary modelling phase. Practical needs necessitate that the method used in this phase is appropriate to the tasks and the time interval available. The SPMM is presented in a way that can be easily understood, and used for structuring and expressing the user's understanding of the cell system requirements. Multiple modelling views are considered necessary to achieve a complete description. Views included in the SPMM are: *Activity, Information* and *Dynamic*.

Principal aspects of Activity, Information and Dynamic modelling of cell systems have been defined and elaborated. These are directed at providing users with a general picture of their nature. Appropriate attributes concerning these aspects have been represented in a tree structure and modelling tables have been developed by following the tree structure. These tables are specifically designed and organised in a structured manner to facilitate users' requirements capture and analysis. They can be used for guiding interviews and recording captured information. Analysis procedures for the resulting models have also been proposed, including analysing the current situation, making proposals for a new or improved system, and indicating the support required for implementation of the proposals.

A computer-aided tool is necessary to support the modelling at the preliminary phase. The SPMM method, presented in this paper, provides a sound basis for the development of the required tool. A prototype tool has been developed and briefly introduced.

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