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ORIGINAL ARTICLE

Study on manufacturing information sharing and tracking for extended enterprises

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Abstract To solve manufacturing information sharing and tracking problems, three key issues are discussed. Firstly, templates are used to host manufacturing information, though they differ in their content and capacity. Secondly, the manufacturing information sharing and controlling method (MISCM) locates every information item at a discrete point on the manufacturing information plane according to its invisibility and unusability. And each user has several various privilege areas in the plane. According to the mapping relationship between the information set and the discrete point set, every user is entitled to access some information items. A template that contains these privileges is activated. Thirdly, when the manufacturing process is in progress, templates are instantiated. Then, a time-dependent instantiated template net (TIT-net) emerges. Based on its searching algorithm, information tracking is achieved through the history view and the in-time view. Finally, some examples show how these issues work together to implement a fluent, controllable and dynamic manufacturing information tracking mechanism.

Keywords Manufacturing information · Templates · Instance · Sharing · Tracking

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1 Introduction

In extended enterprises, manufacturing information sharing is a vital problem. It aims to provide the right information to the right person at the right time in the right format anywhere within an extended enterprise. It contributes to making information flow fluent and the extended enterprise model practical.

Unfortunately, manufacturing resources are dispersed geographically and are variant in their ownership. The structure of an extended enterprise is always complex. Within an enterprise, different roles have different privileges. Besides, owners of manufacturing resources require the protection of their privacy. All of these problems put a barrier across the road to manufacturing information sharing and tracking.

In this paper, to enable a fluent, controllable and dynamic manufacturing information sharing and tracking mechanism, information templates are quoted to formalise and encapsulate manufacturing information. Then the manufacturing information sharing and controlling method, abbreviated as MISCM, is proposed to balance the requirements of information sharing and privacy protecting. In addition, a time-dependent instantiated template net, abbreviated as TIT-net, describes product information's complex structure and dynamic properties. On the basis of a TIT-net searching algorithm, manufacturing information tracking is implemented via the history view and the in-time view.

The rest of this paper is organised as follows. Section 2 presents a brief review of the literature related to manufacturing information sharing and tracking. Section 3 provides an overall architecture of this study. In Section 4, the key technologies and corresponding methodologies are described. Case studies are demonstrated in Section 5, which are followed by our concluding remarks in Section 6.

2 Literature review

In recent years, more and more attention from the academic areas have been paid to manufacturing information sharing and tracking in extended enterprises.

First of all, D'Amours et al. addressed the impact of information sharing between firms of a manufacturing network [1]. Sahina and Robinson measured the value of information sharing and system coordination in a make-to-order supply chain [2].

Furthermore, to enable product information sharing for distributed users, Chan and Chung proposed an enterprise information portal framework [3]. Rezayat created an Enterprise-Web (E-Web) [4]. Solte and Stegmann proposed an approach to federated management of distributed data and services [5]. Johanssona et al. developed a system to enable information sharing and exchange in a whole chain of manufacturing processes [6]. Jansen-Vullers et al. proposed an approach to design information systems for traceability [7]. Under the concept of enterprise integration, Chen and Jan proposed an engineering information management methodology which was based on allied concurrent engineering [8]. Rupp and Ristic proposed a system to support co-operation in complex production networks by enabling companies to determine and exchange supply information with their customers [9]. Sudarsan et al. described a product information modelling framework to support the full range of product lifecycle management (PLM) information sharing [10]. In addition, Zhang et al. used product structure trees to represent product information and product information was organised in vertical levels and horizontal levels [11].

Besides, Web-based technologies such as HTML, Java, XML and VRML have been adopted to implement platform independence and visualize manufacturing information sharing. Among them, Muto developed an XML system to collect and display information for the on-site management of a factory [12]. Krishnamurthy and Zeid proposed a framework and architecture of a mobile-agent-based system to provide mobile information services to the workforce in motion in manufacturing enterprise [13]. Karkkainen et al. presented a product-centric information management approach for managing single-item-level information, in which software agents and peer-to-peer information sharing were used [14]. Estrem regarded Web Services as a key enabling technology to support information integration between enterprises [15].

In summary, most researches presented above focussed on the framework of manufacturing information sharing. Some researchers paid attention to relevant enabling technologies. Few researchers cared about manufacturing information's structure, organisation and dynamic properties. And the requirement of information protection was ignored. It should be noted that the above-reviewed researches have not solved the problems which we mentioned before.

3 Overall architecture

The overall architecture of this study is shown in Fig. 1. Its flow can be described as follows:

1. Manufacturing information is formalised and encapsulated by templates
2. User privileges are taken into account via the MISCM
3. Based on the previous two steps, corresponding templates are activated and template structure trees are instantiated
4. When the machining process is in progress, the manufacturing information is filled into templates dynamically, different TIT-nets emerge
5. Aided by a searching algorithm, template instance sub trees are obtained to provide manufacturing information to users

Therefore, the manufacturing information template, the MISCM and the time-dependent instantiated template net are the key enabling technologies. How they work together will be discussed in the next section.

4 Key enabling technologies

4.1 Manufacturing information templates

All information referring to a manufacturing resource makes up a full information set. Considering different

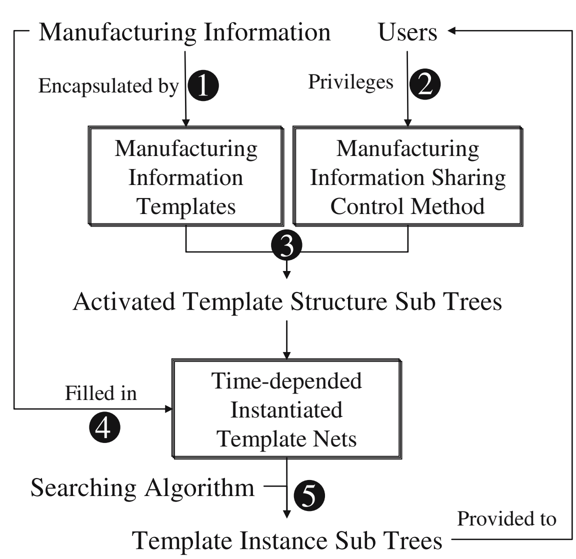


Fig. 1 Overall architecture

configurations, manufacturing information templates were proposed in the e-service model [16–18]. Here, a template is just an information container that defines some information items. Information items included in a template may be just a sub information set or a result of statistics, calculation and analysis of the specific manufacturing data. According to the categories of manufacturing resources, templates can be decomposed into enterprise layer templates, cell layer templates and equipment layer templates.

To implement various manufacturing information configurations, a manufacturing resource may have several templates. Each of them encapsulates certain information from a minimal set to a maximal set. In addition, there are links between different manufacturing resources' templates. In fact, the template structure tree (TST) can describe this phenomenon distinctly. As shown in Fig. 2, a TST is a tree-like network. It inherits the structure of the manufacturing executive sub system. Templates that a user can access connect to each other by links. Then, a template structure sub tree is instantiated. Such a sub tree explains the various configurations of manufacturing information for different users or roles. All sub trees make up a full TST.

4.2 Manufacturing information sharing and controlling method

4.2.1 Basic concepts

As discussed above, there are several templates that are related to a manufacturing resource. These templates vary in their size and contents. But when sending manufacturing information to a user, which template should be chosen? It is the problem that MISCM aims to solve and some concepts are defined as follows.

Definition 1 As shown in Fig. 2, a manufacturing information plane is a two-dimensional plane. Its two dimensions are invisibility and unusability. A manufacturing information plane hosts all information items that belong to a manufacturing resource in a task.

Definition 2 Invisibility defines an information item's impossibility to be viewed by users. It is a decimal fraction that ranges from 0 to 1 and can be obtained by:

$$S = 1 - \frac{x}{k}$$

where S is the invisibility, x is the number of user types that can see the information item and k is the total number of user types.

Definition 3 Unusability defines an information item's derived information item's impossibility to be viewed by users. It is a decimal fraction that ranges from 0 to 1 and can be obtained by:

$$C = 1 - \frac{y}{k}$$

where C is the unusability, y is the number of user types who can see the derived information and k is total number of user types.

Definition 4 An information item's location is determined by its invisibility and unusability. If S stands for its invisibility and C for its unusability, point (S, C) is where it is located in the manufacturing information plane.

Definition 5 Users' privilege areas are some polygonal areas in the manufacturing information plane. They can be decomposed into three types: visible and usable area, invisible and usable area, and visible and unusable area.

Definition 6 An information item may be one of these three categories: basic information item, original information item and derived information item. Among them, basic information items contain static descriptions about manufacturing resources. Original information items contain data directly generated from the equipment. Derived information items derive from the original information items and can be decomposed into simply derived information items and complex value-added information items. Simply derived information items are arithmetical and statistical results of

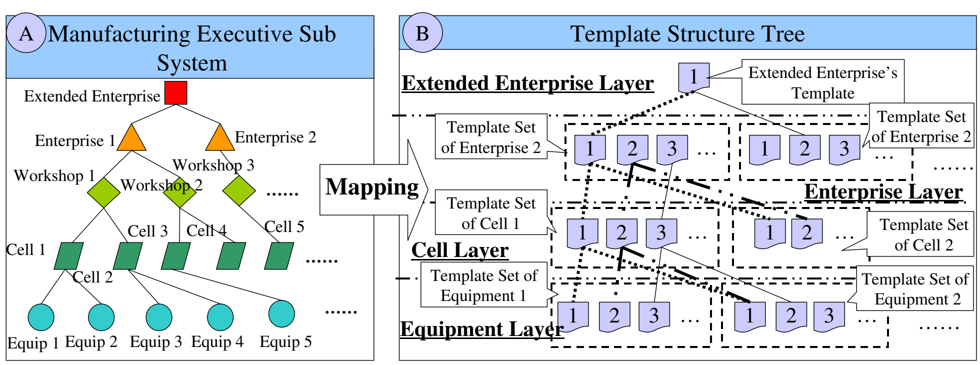


Fig. 2 Template structure tree (TST) example

original information items. Complex value-added information items are the results of data mining and knowledge discovery of the original information items and simply derived information items.

In summary, a manufacturing information plane means a full set of discrete points. Invisibility and unusability stand for the resource owner's requirements of privacy protection. Then, each information item locates at a discrete point in the manufacturing information plane and the relationship between the point set and the information set is established. User privilege areas stand for users' privileges to access manufacturing information. Categories of information items define the derivative relationship between them.

Figure 3 shows an example of a manufacturing information plane. We can see that the user is entitled to access two visible and usable areas, a visible and unusable area, and a invisible and usable area.

4.2.2 Mathematical description of the manufacturing information sharing and controlling method

We introduce $P=\{p_1, p_2, \ldots, p_n\}$ as the set that consists of all discrete points in the manufacturing information plane. We also introduce $I=\{i_1, i_2, \ldots, i_m\}$ as the set that consists of all original information items in the manufacturing information plane. In addition, $U=\{u_1, u_2, \ldots, u_k\}$ is regarded as a set that consists of all user types.

If i_t ($1 \leqq t \leqq m$) is an information item in I, then all user types that can see it make up a set U_t' and all user types that can see information items derived from it make up a set U_t''. According to definitions 2 and 3, the invisibility of i_t can be obtained by $S_t = 1 - \left(\frac{|U_t'|}{|U|}\right) = 1 - \left(\frac{|U_t'|}{k}\right)$ and its unusability is $C_t = 1 - \left(\frac{|U_t''|}{|U|}\right) = 1 - \left(\frac{|U_t''|}{k}\right)$. Meanwhile, point $(S_t, C_t) \in P$ is where i_t locates in the manufacturing information plane.

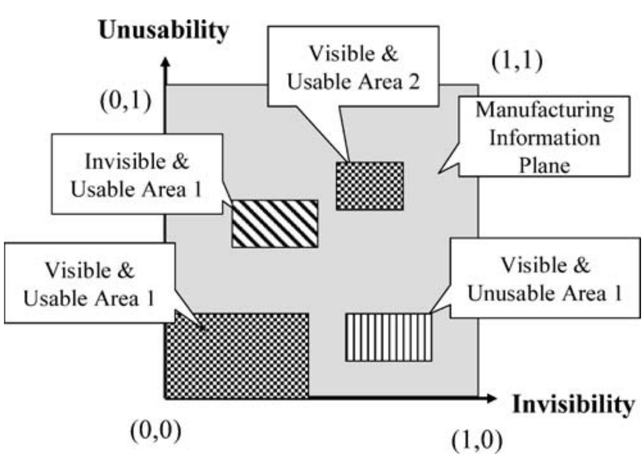


Fig. 3 Example of a manufacturing information plane

If R is a relationship from I to P, an order pair (x, y) in R means that the information item x locates at point y.

The $m \times n$ matrix M_R is R's matrix:

$$M_R = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ \cdots & \cdots & \cdots & \cdots \\ 1 & 0 & 0 & 0 \end{bmatrix}$$

We introduce Q as a non-null point set in the manufacturing information plane and $Q \subseteq P$. We also introduce $\alpha = (a_1, a_2, \ldots, a_n)$ as an n-dimensional vector which can express the relationship between Q and P. And a_i determines whether p_i, a member of P, is a member of Q by:

$$a_i = \begin{cases} 1 & if\ p_i \in Q\ (1 \le i \le n) \\ 0 & other \end{cases}$$

We introduce an m dimensional vector as: $\beta = \alpha \cdot M_R' = (b_1, b_2, \ldots, b_m)$.

According to the rule:

$$if\ b_1 = 1,\ then\ i_j \in S,\ else\ i_j \notin S$$

set S will be obtained. It is a sub set of I and consists of information items located in the area.

4.2.3 Flow of the manufacturing information sharing and controlling method

The MISCM not only defines the mapping relationship between the information set and the discrete point set, but it also formulates a flow to implement it. As shown in Fig. 4, it can be described as an algorithm.

In the algorithm shown in Fig. 4, P is the set of discrete points in a manufacturing information plane and I is the set of original information items. In addition, Q is the set of

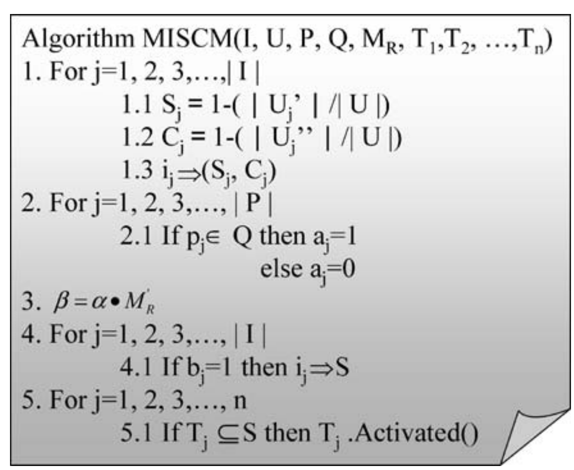

Algorithm MISCM(I, U, P, Q, M_R, T_1, T_2, …, T_n)
1. For j=1, 2, 3,…,| I |
   1.1 S_j = 1-(| U_j' | /| U |)
   1.2 C_j = 1-(| U_j'' | /| U |)
   1.3 $i_j \Rightarrow (S_j, C_j)$
2. For j=1, 2, 3,…, | P |
   2.1 If $p_j \in$ Q then a_j=1
   else a_j=0
3. $\beta = \alpha \bullet M_R'$
4. For j=1, 2, 3,…, | I |
   4.1 If b_j=1 then $i_j \Rightarrow$ S
5. For j=1, 2, 3,…, n
   5.1 If $T_j \subseteq$ S then T_j .Activated()

Fig. 4 Manufacturing information sharing and controlling method (MISCM) flow

Table 1 Users' privileges in three types of information sub sets

	Viewable?	View information that derives from it?
Visible and usable sub set	Yes	Yes
Invisible and usable sub set	No	Yes
Visible and unusable sub set	Yes	No

discrete points in a user privilege area, U is the set of user types and M_R is R's matrix. T_1, T_2,..., T_n are templates. In step 1, the algorithm calculates each information item's invisibility and unusability (steps 1.1 and 1.2). It also locates each information item at a certain discrete point in the manufacturing information plane (step 1.3). In step 2, it decides whether a point lies within the user privilege area or not. In step 3, it decides whether an information item is activated or not. In step 4, all activated information items make up a set. In step 5, if all of the information items in a template are included in template S, the S is activated. All of the activated templates make up a template set and only a template is chosen to encapsulate the manufacturing information for a user. Therefore, a balance of information sharing and protection is achieved.

By default, the MISCM provides default privilege areas for 13 user types. In order, they are designer, chief designer, process designer, chief process designer, manufacturing engineer, cell manager, chief engineer, jobshop manager, enterprise manager, extended enterprise manager, supplier, customer and other user types. In practice, the resource owner can set privilege areas for each user dynamically, considering their requirements, cooperative history and requirements of privacy protection.

According to the types of user privilege areas, the MISCM outputs three information sub sets for each user. They are visible and usable sub set, invisible and usable sub set and visible and unusable sub set. Users' privileges in these sets can be seen in Table 1.

4.3 Time-dependent instantiated template net

4.3.1 Concept of a time-dependent instantiated template net

Template instantiating is a process whereby templates are filled by manufacturing data automatically or manually in the manufacturing execution process. Template instances are its results. As time goes by, templates are instantiated continuously. This phenomenon describes manufacturing information's dynamic changes along the time line. All template instances form a TIT-net.

As shown in Fig. 5, a TIT-net is a three-dimensional network that is derived from the TST. And the time line is vertical to the TST. Template instances with different timestamps are lined up along the time dimension. But, as defined in the TST, links between templates remain unchanged. However, a template instance in the upper level always links to the newest one in the lower level.

4.3.2 Mathematical description of a time-dependent instantiated template net

We suppose that $M=\{m_1, m_2, m_3,..., m_s\}$ is a manufacturing resource set. A manufacturing resource in it has no more than k templates. Then, the relationship between a

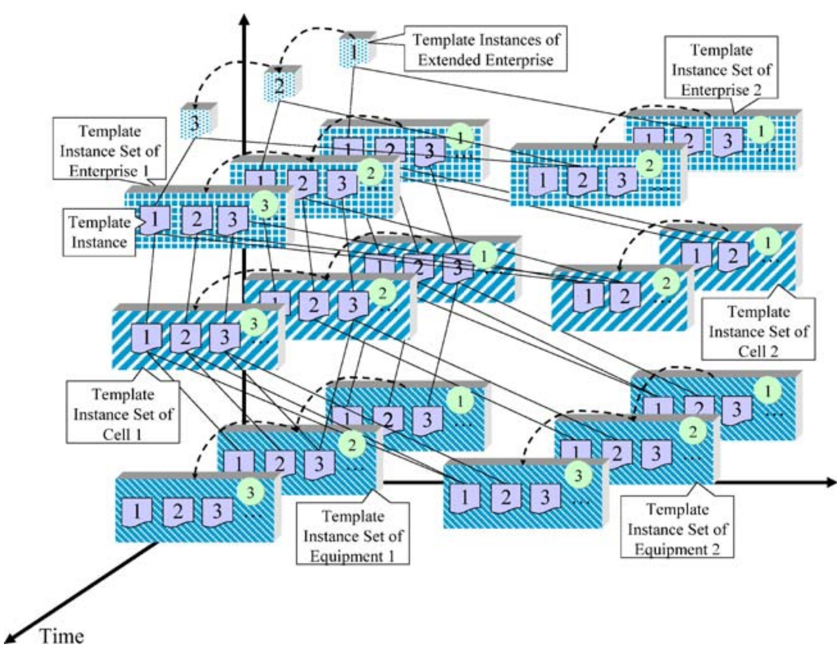


Fig. 5 Example of a time-dependent instantiated template net (TIT-net)

Table 2 List of manufacturing information items

Original manufacturing information items	Derived manufacturing information items	*Invisibility* (user types that can see it)	*Unusability* (user types that can see its derived information item)
Task info		0.154 (1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11)	0.461 (4, 5, 6, 7, 8, 9, 10)
Finished procedure	Finishing rate	0.615 (5, 6, 7, 8, 10)	0.615 (5, 6, 7, 8, 10)
Count of procedures		0.461 (3, 4, 5, 6, 7, 8, 10)	0.538 (4, 5, 6, 7, 8, 10)
Current NC code		0.692 (5, 6, 7, 8)	0.846 (6, 7)
Current procedure		0.692 (5, 6, 7, 8)	0.846 (6, 7)
Operator		0.692 (5, 6, 7, 8)	0.846 (6, 7)
Quality control data	Quality control chart	0.769 (5, 6, 7)	0.846 (6, 7)
Errors		0.769 (5, 6, 7)	0.769 (5, 6, 7)
Cutting speed	Machining status	0.769 (5, 6, 7)	0.769 (5, 6, 7)
Cutting depth		0.769 (5, 6, 7)	0.769 (5, 6, 7)
Feeding rate		0.769 (5, 6, 7)	0.769 (5, 6, 7)
Spindle speed		0.769 (5, 6, 7)	0.769 (5, 6, 7)
...	...	...	...

user and all templates can be described by an $s{\times}k$ matrix M_t:

$$M_t = \begin{bmatrix} 1 & 0 & 0 & \cdots & 0 \\ 0 & 1 & 0 & \cdots & 0 \\ 0 & 1 & 0 & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & 1 & \cdots & 0 \end{bmatrix}$$

The rows in M_t stand for the manufacturing resources and the columns for their templates. The cell entries in M_t dictate whether the user can access certain templates. In detail, 1 stands for yes and 0 for no. According to the MISCM, every row in M_t has no more that one entry of 1.

We also suppose that there are j counts of 1 in M_t. Then, set $T=\{t_1, t_2, t_3,..., t_j\}$ ($j \geq s$) consists of templates that the user is entitled to accordingly. The relationship between templates can be described by V, a binary relationship of T. Suppose M_v is matrix of V as follows:

$$M_v = \begin{bmatrix} 0 & 1 & 1 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & 0 \\ 0 & 1 & 0 & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & 1 & \cdots & 0 \end{bmatrix}$$

The cell entries in M_v stand for the relationship between templates. If the entry that lies at the crossing of template t_a and t_b is 1, the t_a links to t_b.

Suppose template t_a has p instances, which make up a set $W_a=\{w_{a1}, w_{a2}, w_{a3},..., w_{ap}\}$ and template t_b has q instances, which make up a set $W_b=\{w_{b1}, w_{b2}, w_{b3},..., w_{bq}\}$. A relationship from W_a to W_b stands for the relationship between instances of t_a and t_b. Element (w_{ai}, w_{bj}) in C denotes that, w_{ai}, an instance of t_a, links to w_{bj}, an instance of t_b. The matrix of C, M_c is shown below:

$$M_c = \begin{bmatrix} 1 & 1 & 0 & \cdots & 0 \\ 0 & 1 & 1 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & 1 & \cdots & 1 \end{bmatrix}$$

4.3.3 TIT-net-based searching algorithm

A TIT-net describes the manufacturing information's dynamic changes along the time line. This phenomenon makes the TIT-net a complex net and throws impediments to obscuring the way to manufacturing information tracking. To solve these problems, a depth first searching (DFS) algorithm is adopted. Its main steps are quoted as follows:

– Algorithm TIT-searching (u, r):

– Step 1: t=getTemplate(u, r)
– Step 2: m=t.getLinkCount()
– Step 3: n=t.getInstanceCount()
– Step 4: for i=1, 2, 3,..., n

– Step 4.1: instance=t.getInstance (i)
– Step 4.2: instance.output()

Table 3 Some users' privilege areas

Users	Visible and usable area	Invisible and usable area	Visible and unusable area
Extended enterprise manager	(0, 0), (0.5, 0.5)	(0, 0.5), (0.65, 0.65)	–
Enterprise manger	(0, 0), (0.95, 0.9)	–	–
Cell manager	(0, 0), (0.7, 0.8)	–	(0.3, 0.8), (0.9, 0.9)

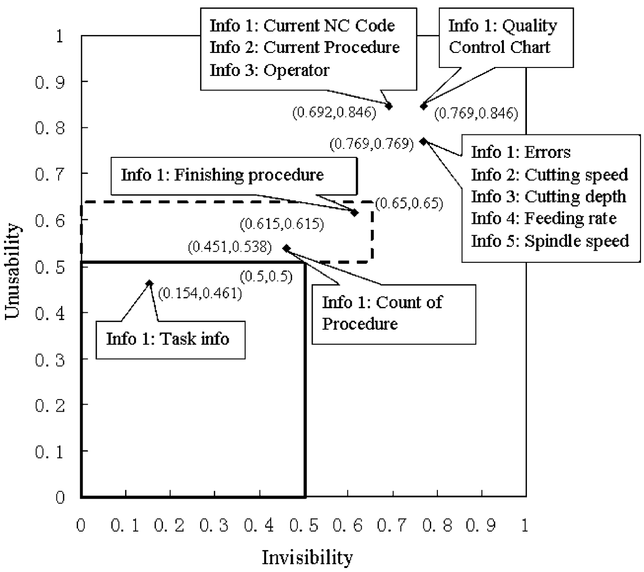


Fig. 6 Example of a manufacturing information plane

– Step 4.3: for j=1, 2, 3,..., m

– Step 4.3.1: instance.linkTo(j)

In the algorithm, u is a user and r is the manufacturing resource to be tracked. In step 1, according to the MISCM, the algorithm receives a proper template for the user. Then, it acquires the template's number of instances and low-level links (step 2 and step 3). In step 4, the algorithm outputs all of the template's instances (step 4.2) and low-level links (step 4.3) in order. The routine linkTo() implements outputting a template instance's low-level instances. Its main steps include:

– Routine linkTo (j):

– Step 1: instance=getLink(j)

– Step 2: instance.output()

– Step 3: m=instance.getLinkCount()

– Step 4: for j=1, 2, 3,..., m

– Step 4.1: instance.linkTo(j)

In step 1, we can obtain a template instance, which is numbered j. Then, the routine outputs its instance (step 2) and obtains its number of links (step 3). By calling itself recursively, the routine outputs the instance's low-level instances in order (step 4).

5 Case studies

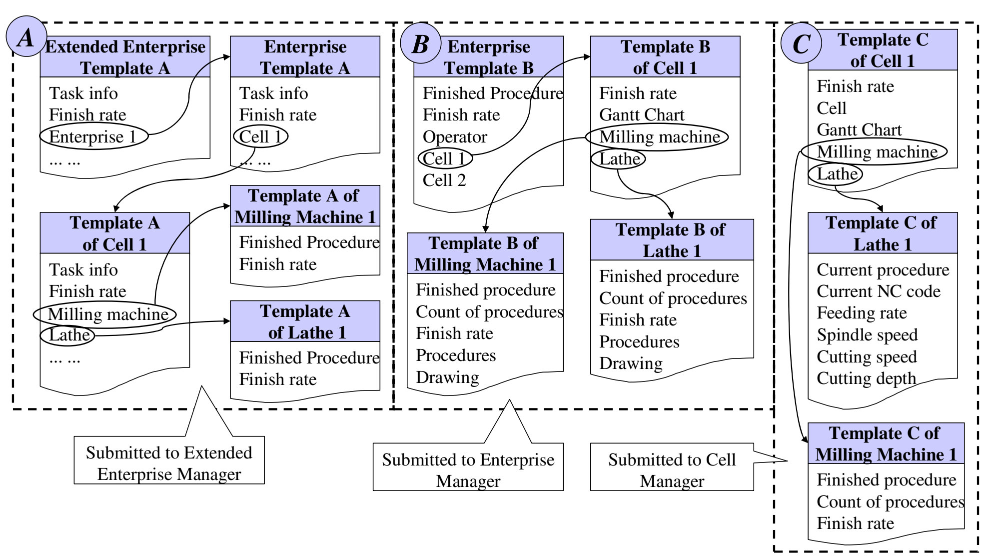
In a pump machining process, the related manufacturing information items are quoted as follows. As shown in Table 2, each original manufacturing information item has its own invisibility and unusability levels, and several original manufacturing information items may derive a derived manufacturing information item.

Table 3 shows the privilege settings for some users. We can see that the cell manager has a rectangle visible and usable area that has a diagonal from point (0, 0) to point (0.7, 0.8), and his visible and unusable area is a rectangle that has a diagonal from point (0.3, 0.8) to point (0.9, 0.9).

According to Tables 2 and 3, a manufacturing information plane and the extended enterprise manager's privilege areas are configured and shown in Fig. 6. The extended enterprise manager's visible and usable area is enclosed by solid lines, and his invisible and usable area is enclosed by dashed lines. Information items that lie within these two areas are what the extended enterprise manager can access in this task. They will activate corresponding templates to formalise and encapsulate manufacturing information for him.

In Fig. 7, part A shows a template sub tree for the extended enterprise manager. Parts B and C show template

Fig. 7 Example of a template structure sub tree



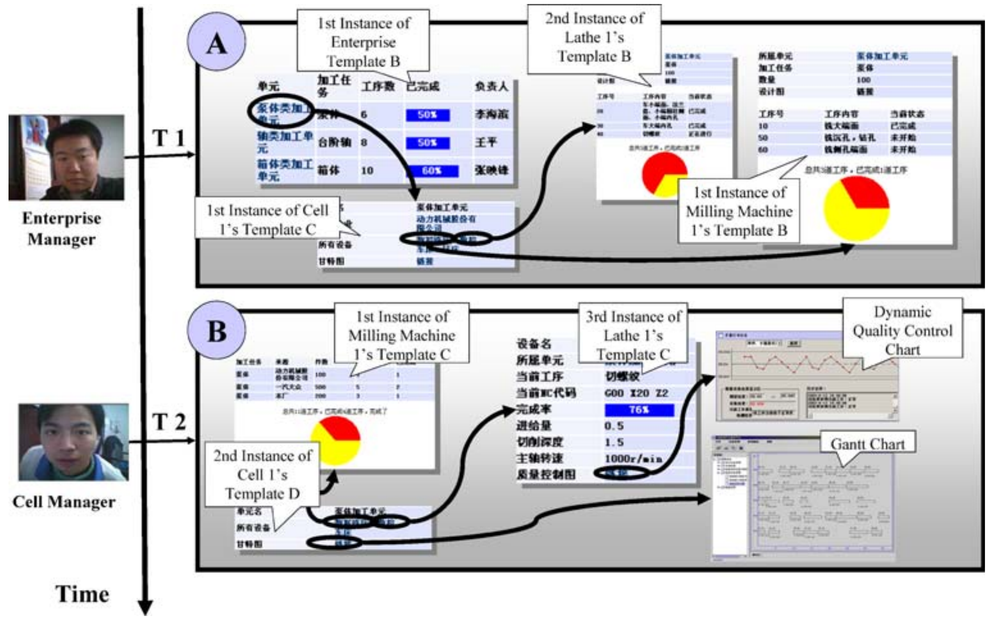


Fig. 8 TIT-nets for the enterprise manager and the cell manager

sub trees for the enterprise manager and the cell manager, respectively.

In Fig. 8, part A shows a TIT-net for the enterprise manager and part B shows a TIT-net for the cell manager. We can see that these two nets differ in their structure and content. The cell manager can access more detailed information. He is even entitled to view the quality control chart and the Gantt chart. This phenomenon explains the manufacturing information's diverse configuration for different users.

Figure 9 shows a TIT-net for the extended enterprise manager. As shown in the figure, he tracked the machining process twice. For the first time, he can see the sub net in part A. For the second time, he can see the sub net in part B. These two nets have the same structure but different contents. This phenomenon demonstrates the dynamic changes of manufacturing information.

Compared with the literature [3–10], this paper does not propose any manufacturing information sharing frameworks. It instead focusses on manufacturing information's

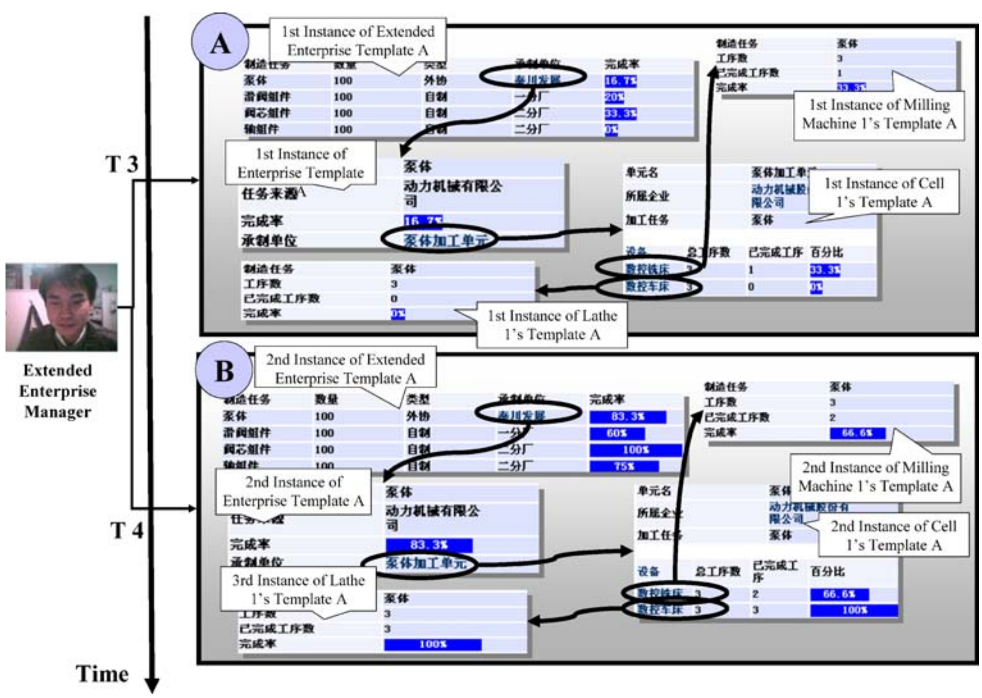


Fig. 9 TIT-net for the extended enterprise manager

organisation structure and dynamic properties, and conflict between the requirements of manufacturing information sharing and privacy protection in extended enterprises. And compared with the product structure tree proposed in the literature [11], the TST extends it greatly by adopting templates to implement information's various configurations and formalisations. It is difficult to find some idea or method similar to the MISCM and TIT-nets in the referred literature. Web-based technologies studied in the literature [12–15] can also be adopted to implement the methodologies proposed in this paper.

6 Concluding remarks

Instead of constructing a manufacturing information sharing framework or platform, this paper puts forward a manufacturing information sharing and tracking method. Manufacturing information templates, the manufacturing information sharing and controlling method (MISCM) and time-dependent instantiated template nets (TIT-nets) are regarded as the key enabling technologies and are discussed in detail. Finally, some running examples show how these technologies work together to provide a practical approach to manufacturing information sharing and tracking.

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