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Manufacturing Goal Decomposition As A Means Of Structuring Co-Operative Control Systems

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Abstract

This paper addresses a theme which is common to a number of IMS endeavours, namely that of managing and achieving production goals within a co-operative manufacturing framework. The work is particularly relevant to developments in the IMS Holonic Manufacturing Systems[1] (HMS) and Next Generation Manufacturing System[2] (NGMS) Projects. A study of academic and practical methods for goal and task decomposition is made, and is used to raise issues about potential limitations on co-operative control methods. An industrial case study is used to illustrate these issues.

Keywords: co-operative control, distributed manufacturing system, goal decomposition, task decomposition, task allocation.

1. BACKGROUND TO CO-OPERATIVE CONTROL SYSTEMS IN MANUFACTURING

1.1 Co-operative Control Systems

Co-operative control systems describe an emerging class of approaches to managing distributed processes and functions. A common feature of these approaches is that they do not employ conventional centralised strategies for breaking down (decomposing), allocating and executing tasks but seek to allocate and complete tasks via interactive co-operation with local resources or production units. Specifically this means an interactive (typically negotiated) form of decomposition and allocation between the specified task and the local resources. This is coupled with a co-ordinated but distributed management of the execution of tasks without control via a centralised command – response mechanism.

By way of reference, some of the common co-operative control approaches are outlined below:

- Multi-agent systems [see Wooldridge, M.J., Jennings, N.R., (1995) and the references therein] - originating within the distribution artificial intelligence (DAI) field of computer science. Based on the concept of autonomous software entities empowered with an ability to

[1] http://hms.ifw.uni-hannover.de/

[2] http://www.ngmnet.org/ngms/ngmsintr.htm

propose, interpret, decompose, select and address tasks. The agent's actions are directed by local goals assigned to or acquired by that agent. Global behaviour emerges with agent interaction.

- Distributed Problem Solving [see Bond, A.H., Gasser L.(Eds.), (1988) and references therein] - also part of DAI, reflecting a centralised decomposition of tasks and co-ordination of their execution, with local distributed units capable of local problem execution and resolution.
- Holonic Manufacturing Systems [Agre et al (1994), Valckenaers et al (1994), Christensen (1994)] – addressing the specification and development of components for autonomous, co-operative manufacturing control systems. These systems are intended to reflect features of both multi-agent behaviour and distributed problem solving in that decomposition and allocation of tasks can have both centralised and distributed components, and that execution be co-ordinated in a manner that reflects centralised and distributed methods. Additionally, this research is investigating aspects relating to operating, monitoring and maintaining [McFarlane, D., et al (1995)] physical manufacturing hardware which are not immediately relevant in this paper.
- Next Generation Manufacturing Systems [Bunce, (1996)] – examining the role of autonomous, distributed building blocks within a manufacturing enterprise and methods for their integration via a number of approaches including a replication of biological processes. A co-operative behaviour emerges from such an operational approach.
- Empowered (Hoshin – Kari) Teams [Akao, Y., ed. (1991). Eureka, W. E. and N. E. Ryan (1990)] - team-based manufacturing environments provide opportunities for co-operative (human-based) control in the allocation and execution of tasks between teams and individuals. In practice it has been observed that intra-team co-operation is successful, but inter-team co-operation is often limited due to physical separation and restricted information availability.

One of the principal reasons for the development of these approaches is that co-operative control systems potentially provide a greater ability to respond to unexpected disruptions. This paper begins to examine conditions under which this should be the case.

1.2 Properties of Co-operative Control Systems

Following the examples cited in the previous section we now provide a (provisional) set of properties that characterise a typical co-operative control system in a manufacturing context.

P1: Distributed control capabilities for local production units.
P2: Decision-making capability at the production unit level, driven by knowledge of goals and production unit capability, and with limited reliance on central command/response.
P3: Partial awareness only of global production situation from local unit.
P4: Co-operative task decomposition and allocation involving interaction (e.g. negotiation) between local production units and/or central co-ordination function
P5: Goals for production units are set locally, but must be compatible with the global operational goals.
P6: A local, though co-ordinated, approach to task execution and completion.

Properties P2, P4, P5 and P6 introduce the focus for this paper, which involves a preliminary investigation into manufacturing goal and task decomposition and allocation practices and their compatibility with co-operative control operation.

In the next section we review approaches to goal decomposition; both as they are addressed in theory and in practice. We then demonstrate how theoretical methods can be used to interpret industrial goal and task assignment and whether this is compatible with co-operative control system development. This paper is intended to highlight issues for goal assignment and task management in co-operative manufacturing. Underlying mathematical analysis will follow in a more detailed version of the paper.

2. GOAL DECOMPOSITION APPROACHES - THEORY AND PRACTICE

Goal decomposition (in a manufacturing context) refers to the systematic breakdown of production goals into simpler, more specific subgoals which may be used to generate executable tasks, allocate them to resources and integrate their execution in a manner which achieves the goals.

2.1 Theoretical Goal and Task Decomposition Approaches

Goal and task decomposition has been studied within the field of Distributed Artificial Intelligence (see Bond & Gasser 1988, Uma et al. 1996). Distributed Artificial Intelligence is concerned with the distributed and parallel operation of agents, which are computational entities with some ability to reason, interact with each other and act within a shared problem domain. Such approaches have been developed for environments where agents may have different capabilities, physical locations and/or have access to different data. There are potential performance advantages over centralised problem solving approaches due to the ability of agents to respond more rapidly to changes in local behaviour, without incurring the delays associated with consulting a central control node.

2.1.1 Methods from Distributed Problem Solving and Multi -Agent Systems

As discussed in Section 1, two subfields of DAI are of interest: Distributed Problem Solving and Multi-Agent Systems. Distributed Problem Solving is concerned with the solution of problems by a set of agents which are generally designed specifically to solve a particular set of problems. Generally agent goals are identical or are known to be compatible. Multi-Agent Systems is a related but slightly broader field in which agents may have different problem/domain descriptions, individual and/or shared goals and different architectures. Whilst task decomposition must be carried out in both cases, in general it is more difficult in the case of multi-agent systems due to the possibility of no initially shared problem description or the possibility of non-global goals (see Uma et al 1996).

2.1.2 Decomposition within a Distributed Problem Solving Framework

A comprehensive framework for distributed problem solving is presented by Yang & Zhang (1996). Distributed problem solving is understood in that paper to consist of four phases which must be brought together: task division/decomposition, task allocation, problem solving and solution integration.

- Task division and decomposition are means whereby smaller tasks are generated from an original task. In the context of the present paper, this process is driven by production goals.

For example, orders may need to be divided into batches and production steps, to which production resources can be readily assigned.

- Task allocation is the process of assigning agents to specific tasks. Having decided the necessary batch sizes and production steps, decisions must be made concerning the allocation of production equipment to these tasks.
- Problem solving is the domain-dependent means by which agents obtain a solution for the tasks assigned to them. In the manufacturing context, this consists of each production unit fulfilling the production task assigned to it.
- Solution integration is the process that collects and integrates a set of solutions to tasks, to form a comprehensive solution to an original task. In the manufacturing context, this is fulfilled via material flows and co-ordination between different production units whose tasks together fulfil a production order.

There are implicit interrelationships between the above phases. A task division/decomposition must result in smaller tasks which are defined in such a way that they can be allocated to and executed by pre-existing agents. In addition, the smaller tasks must be defined so that their results can be readily integrated. Thus task division and decomposition must be done in such a way that sub-task allocation, problem solving and integration are achievable under foreseeable circumstances.

It should be noted that each of the above four phases are themselves tasks which can be carried out by one or more agents. In many existing production systems, decomposition, allocation and integration are arranged centrally and unit problem solving is reduced to fairly simple task execution. Thus local unit goals reduce to the execution of tasks on command and no higher level goal description is required by the production unit. However, when the low level task can no longer be fulfilled due to unforeseen production conditions (e.g. breakdown of an upstream or downstream machine), the production unit may be forced to make a local decision before advice from a central node becomes available. Recently, it has been proposed that production units be invested with enhanced reasoning and communication capacities to enable them to participate in decomposition, allocation and integration decisions. However, in order to make such decisions, these units must be driven by more sophisticated local goals. This should enable the units to deal in a reasoned manner with changing circumstances.

2.1.3 Strategies for Solving the Decomposition and Allocation Problem

Uma et al (1996) highlight the apparent lack of formalisms for carrying out problem decompositions, commenting that it is generally assumed in the distributed artificial intelligence literature that a problem has already been decomposed and that the more prevalent topics in the literature concern agent control, co-ordination, synchronisation and integration issues.

Yang & Zhang propose that there are four different ways in which tasks may be dealt with. Whilst, these problem solving strategies may be applied directly to manufacturing problems, they may in turn be applied to the task of decomposing and allocating production tasks:

1 Task Unique Allocation and Problem Solving

A task is allocated to a single agent which finds a solution. This is true of many centralised planning algorithms.

2 Task Multi-allocation and Solution Synthesis
The task may be allocated to multiple agents who each provide a different solution to the same problem. These solutions are then synthesised to produce a single solution to the overall problem. This may involve resolving disparities between the individual results. This might correspond to competitive schedulers, each putting forward schedules which are then compared in some agreed manner and then adopted.
3 Task Division and Solution Construction
A number of partial tasks are created which together fully describe the original task. A solution can be constructed from the partial-solutions, provided they meet so-called domain or consistency constraints. The problem solving and solution construction steps may need to be iterated. An example is given of a distributed information retrieval system to support machine design in which agents retrieve sub-component designs which must match at their interfaces. This may correspond to machines, each with their own schedule generators, which may need to resolve conflicts through negotiation, due to the need to synchronise their plans or ensure that a common resource can be shared.
4 Task Decomposition and Solution Composition
A number of sub-tasks are created which are simpler than the original task, however sub-solutions cannot be simply aggregated to form a solution of the original task. Instead the sub-solutions must be composed in order to form a solution to the original problem. As explained by Yang & Zhang, "(composition) is a high-level decision-making process which requires the sub-solutions as its supporting data". An example is given of doctor using available data from various diagnostic tests to make a diagnosis of a patient. This corresponds to having a centralised scheduler which solicits partial schedule information from units and then synthesises a single schedule from the partial information.

2.2 Industrial Goal Breakdown

The basic goals of any production operation are generally as simple to express as:

- quality - production of required product within specification
- cost - producing in such a way as to maximise profit / minimise costs
- time - achieve time based targets for delivery, production

In fact quality is frequently taken as assumed in many instances.

Any additional goals set tend to be viewed as derivatives of or constraints on the above, and the main differentiation occurs in the way in which the responsibility for these goals is distributed / decomposed across personnel and production units in a plant.

Global goals may only reside explicitly in a single location (often production planning) which attempts to decide sub-tasks and allocate them according to global goals. In order for a production system to sustain its output, sub-task generation and allocation must be carried out dynamically according to changing production conditions. This may still be achieved centrally, however there is now consensus that gains can be made through decentralising these functions. However, the mechanisms for achieving these gains are not well understood. Indeed, this paper intends to lay foundations for the development of systematic methods of deriving such dynamic task generation and allocation procedures.

Note that:
(1) A sub-goal (local goal) can potentially contribute to more than one global goal e.g. machine quality performance affects both cost and delivery goals
(2) Stand-alone sub-goals exist which are meaningful only for a single production unit, and which only indirectly contribute to global goals.
e.g. good housekeeping and maintenance
(3) In most systems, goals are translated into tasks under certain assumptions on operating conditions. Tasks are only reviewed periodically or under exceptional circumstances.
e.g. deciding production orders in a make-to-stock company based on foreseeable production capacity and forecast demand. When demand for a certain product increases sharply, rapid re-scheduling may be required.
(4) Independently set subgoals may, at times, be in conflict with global goals.
e.g. increasing machine throughput may actually compromise overall production throughput when it exhausts a previous buffer, leading to forced shut-down of the machine. The machine shut-down may lead to a very severe impact on overall throughput.

3. ANALYSIS OF PRODUCTION TASK AND GOAL DECOMPOSITION

Based on the observations in the previous section we now propose a framework for considering task decomposition and allocation within a manufacturing production context. The aim of the framework is to indicate how tasks are allocated in both a conventional and co-operative operation and to demonstrate the role of production goals in each case. The framework will then be illustrated via an industrial case study to show the potential requirements for co-operative resource allocation compared to the existing allocation process.

3.1 A Framework For Examining Manufacturing Task Allocation

The framework presented here is preliminary in nature and seeks to address only the task decomposition and allocation issues raised in Section 2. That is, issues associated with task execution are beyond the scope of the paper. We present the framework in two forms:
(i) Conventional Task Decomposition and Allocation
(ii) Conventional Task Decomposition with Cooperative Allocation

(i) *Conventional Task Decomposition and Allocation* – This approach is intended to represent a typical manufacturing operation based on a centralised scheduler. (Refer to Figure 3.1) In this situation, the production goals in conjunction with customer orders generate specific production task(s).

e.g.	GOAL 1:	mimimise cost per unit
	GOAL 2:	ensure prompt delivery
	ORDER:	provide to customer x items by Friday 5pm at £1.20 per item
	=>	
	TASK:	produce x items at £1 per item or less by Friday 12pm

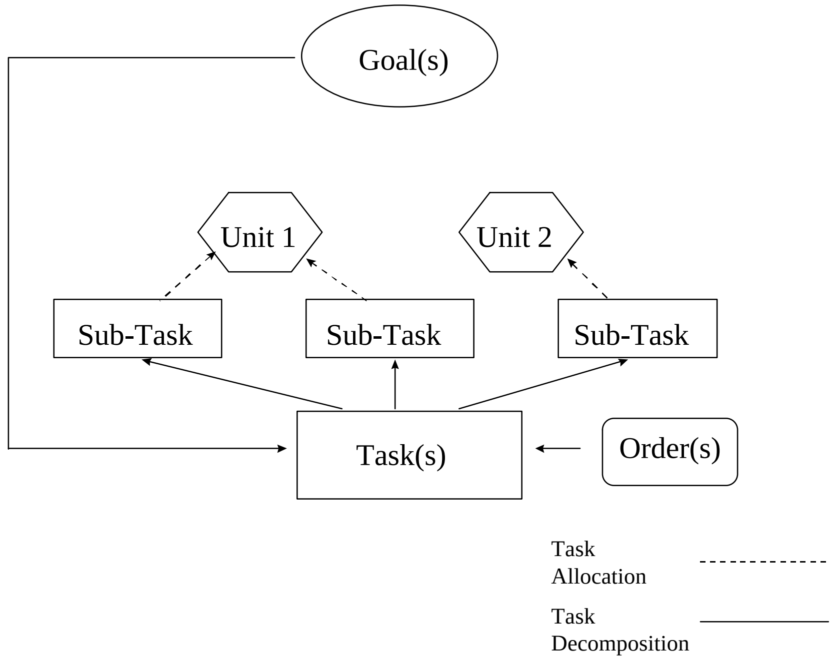

Figure 3.1 Conventional Task Decomposition and Allocation

These tasks are then decomposed into a number of sub-tasks in order that the individual production units are capable of addressing the task

e.g. SUB-TASK 1: prepare x items at £.0.33 per item by Friday 9am
SUB-TASK 2: mix x items at £0.33 per item by Friday 10am
SUB-TASK 3: pack x items at £0.33 per item by Friday 11am.

The sub-tasks are then allocated to production units (resources) based on their capability and availability to complete the sub-tasks as required. Clearly the example above is oversimplified in the sense that there will typically be a number of tasks to be addressed at once. The selection of resource in the allocation of sub-task can often be trivial owing to a limited overlap of capabilities between units, while the time dependencies of tasks makes sequencing more difficult to achieve.

(ii) *Conventional Task Decomposition with Cooperative Allocation* - This approach is intended to represent the first step of the migration of a typical manufacturing operation towards co-operative control. (Refer to Figure 3.2) As above, the production goals in conjunction with customer orders generate specific production task(s), and these are decomposed into sub-tasks compatible with the individual production units. However, the goal(s) are also decomposed into sub-goals of a form which can direct co-operative sub-task allocation (and subsequent) execution by the production units. That is, based on these sub-goals, and on consideration of the unit capabilities and availabilities, the individual units bid for or request appropriate sub tasks.

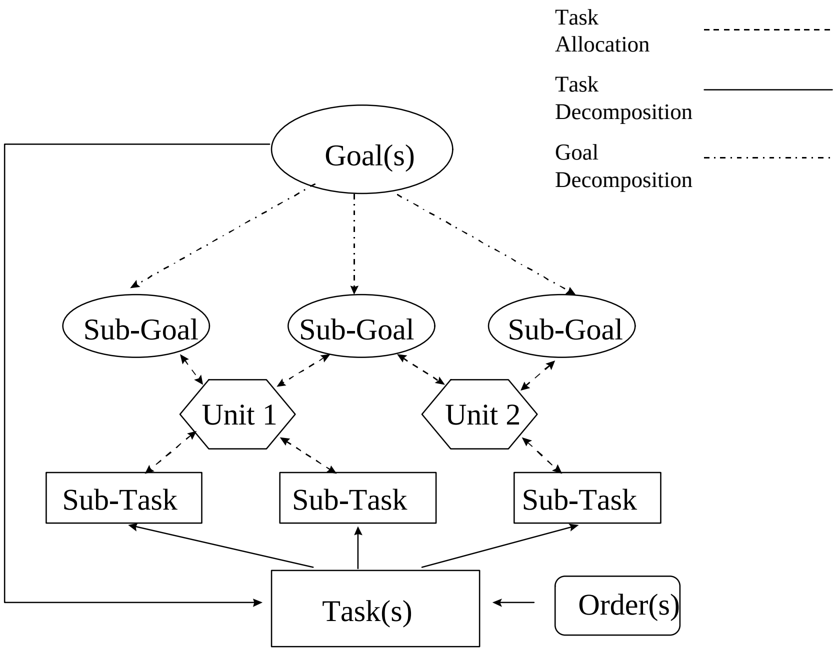

Figure 3.2 Conventional Task Decomposition with Co-operative Allocation

The critical difference between (i) and (ii) is that units are able to influence the type of sub-task they undertake depending on their (dynamic) capability. It is conceivable that a set of sub-tasks might in fact be incompatible with the available production capability in which case a new task decomposition would be required.

The benefit from this approach is that the production units will select sub-task that are directly compatible with their capabilities, availability and local goals at the time of allocation. Consequently a degree of adaptability and/or robustness is achieved in the face of unexpected operating conditions or disruptions.

An open research issue is highlighted here which is the impact of the relationship between sub-goals and the main production goals. We note that issues such as a) conflict b) overlap and c) orthogonality of goals can greatly influence the chance of achieving an effective fullfilment of the task in terms of the main production goals.

In the next section we assess this framework in terms of the actual task allocation processes of an industrial collaborator.

3.2 Illustrative Industrial Goal and Task Decomposition

In this section we assess the framework of Section 3.1 in the context of a typical steel making plant in which a conventional approach to task decomposition and allocation is currently employed. A detailed presentation of this was given previously in Matson et al (1997).

The diagram in Figure 3.3 is illustrative of the approach used for allocating batches of steel to the two steelmaking production lines that it contains. Comparing Figure 3.1 and 3.3, it can be seen that a production task is generated from an order for a quantity of billets and by consideration of the main two production goals of cost minimisation and timely delivery. For a given task, batches of steel are planned (sub-tasks) which are then allocated to one of the two production lines depending on availability and on the capabilities (quality, production rate) required for the particular batch[3]. The two lines differ in both capabilities. It is noted that in this case the task allocation function needs to be also aware of specific cost goals as these can significantly influence the sequence of batches allocated to the different lines. Time allocation is the most complex issue for this allocation function.

A potential shortcoming of this procedure is that, the planning function occurs under the assumption of perfect operating conditions, which cannot always be adhered to. Under breakdown circumstances it is often necessary to make local improvisations at the production unit level which deviate significantly from plan.

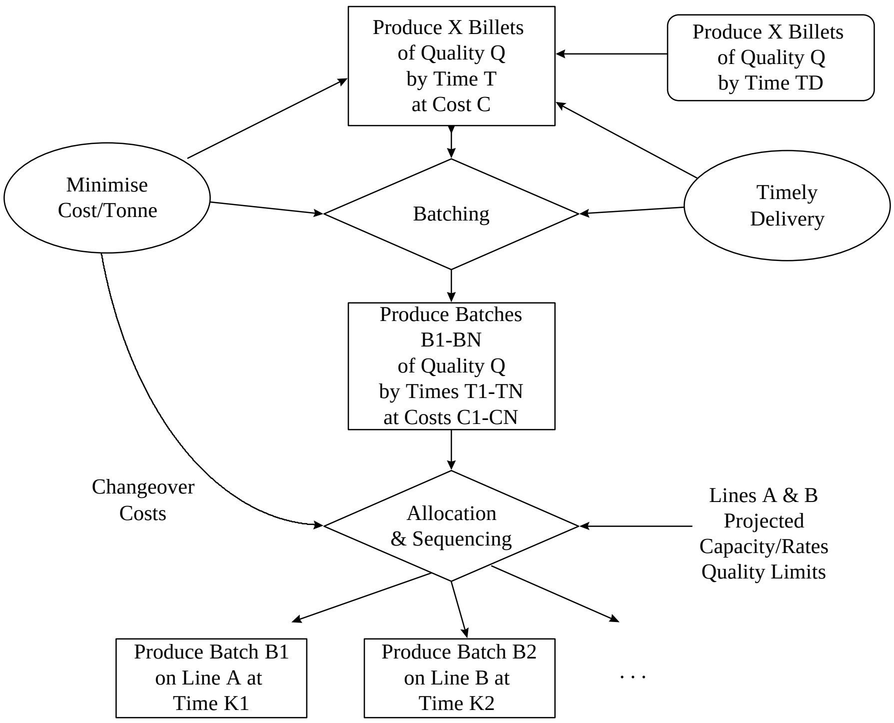

Figure 3.3 Conventional Task Decomposition / Allocation at a Steel Making Plant

We will now to consider how the task allocation might operate under the Conventional Task Decomposition and Co-operative Allocation scheme of Figure 3.2. Figure 3.4 illustrates a representative breakdown of the two production goals introduced into Figure 3.3 combined with the task allocation of Figure 3.2. An observation about the goal decomposition in Figure 3.3 (following from Section 3.1) is that all of the sub-goals underlying the two main

[3] We note here that the task decomposition described is in fact a subset of the overall decomposition that is typically made. In fact each of the two production lines comprise a number of production units – e.g. furnace, caster etc - and the individual consideration of these would lead to a further decomposition of the sub-tasks into more appropriate sub-tasks – e.g. Produce Cast x of Quality Q by time T1c at cost C1c etc.

production goals are essentially compatible with each although trade-offs would begin to occur beyond certain limits. E.g. maintenance versus productivity sub-goals. Additionally, referring to Section 2.1.3, the task decomposition we are dealing with is one of task division rather than task decomposition which implies that a co-operative resource allocation – at least at the level of the production line – should be possible.

The co-operative allocation scenario of Figure 3.4 would be as follows: Lines A and B are presented with sub-tasks of the form outlined in Figure 3.3 (i.e. Produce Batch B1-BN …). Each Line assesses its availability – in discrete time slots as a first approximation – and notes its current capability in terms of quality requirements and also production rate, and assesses the possibility of undertaking different batches by reasoning about the effect of each on its relevant sub-goals. The task allocation occurs as each line assigns itself the sub-tasks it is best suited for[4]. A change in availability and / or capability (e.g. due to breakdown) would limit a Line's availability to bid successfully for batches and they would be allocated to the other Line assuming it had suitable availability.

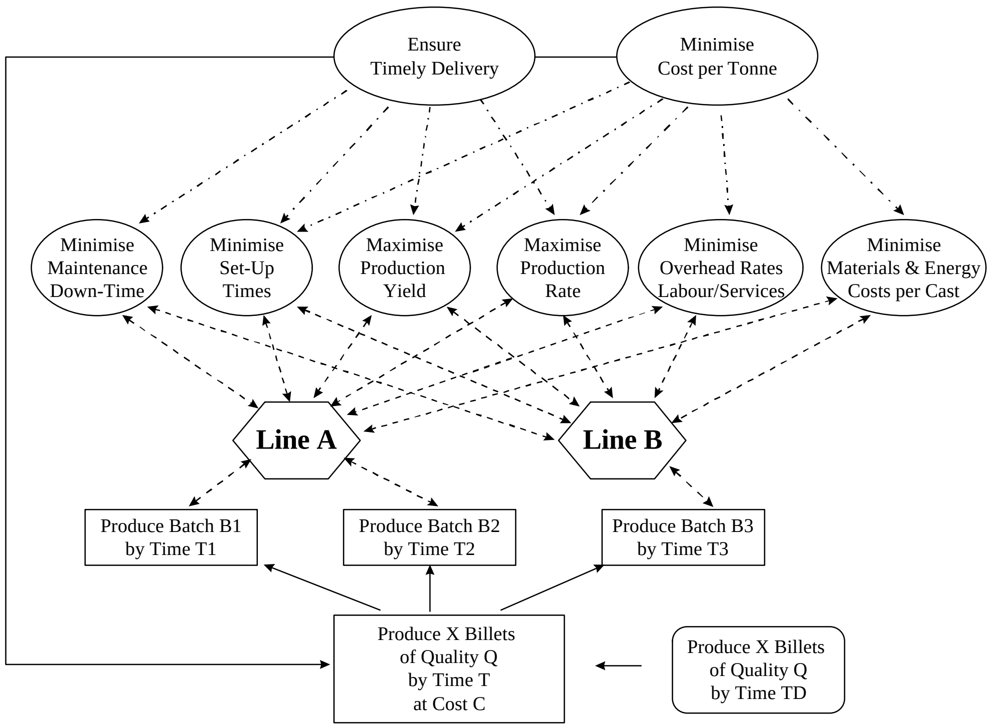

Figure 3.4 Conventional Task Decomposition with Co-operative Allocation for Steel Making Plant (Illustrative Only)

[4] Note that the concept of a *selfish* production unit - discussed in the agent literature - is not relevant here as individual production units are fundamentally *unselfish!*

4. TOWARDS FULL CO-OPERATIVE CONTROL

The framework presented in Section 3 presents a first step towards a completely co-operative environment (although many issues remain unresolved about the performance of such systems). Referring to items (i) and (ii) in Section 3.1, a further step is to consider an environment in which task decomposition and allocation are both performed co-operatively:

(iii) *Co-operative Task Decomposition and Allocation* - In this situation, the goal(s) are decomposed into sub-goals which govern the task decomposition, allocation (and execution) of the production unit operations. Based on these sub-goals, and on production unit capabilities and availability, the units are able to interpret the production task, propose a bid for or request appropriate sub-tasks. Task decomposition and allocation are both co-operative in this case. Based on their goals and depending on their (dynamic) capability the units are able to influence the way sub tasks are developed and the type of sub task they undertake. Such an approach affords the maximum resilience to changing conditions and disruptions and in many ways reflects the intended operations of the holonic systems approaches and manufacturing based multi-agent systems discussed earlier.

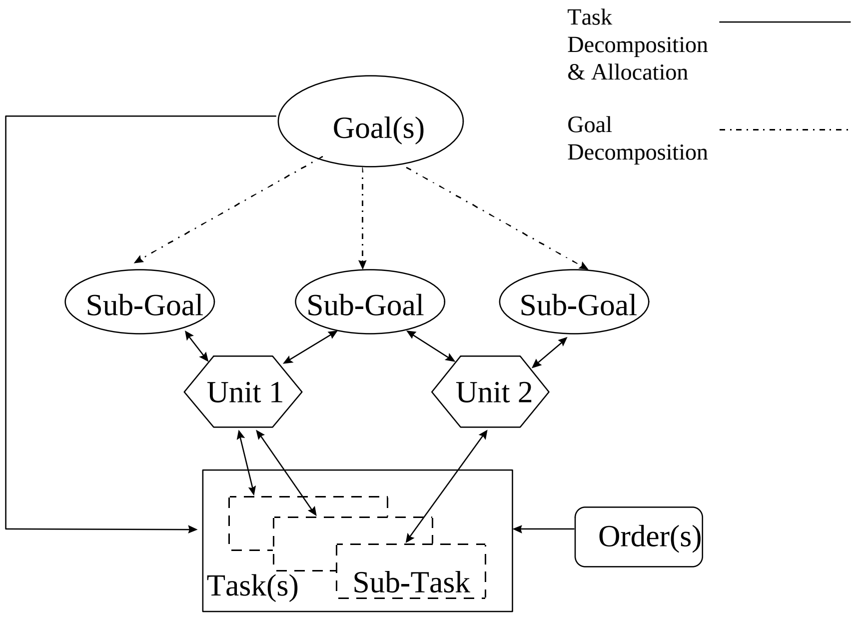

Figure 4.1 Co-operative Task Decomposition with Allocation

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