A Reference Activity Model for Smart Factory Design and Improvement

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A complete set of the activity models described in this paper is available at https://www.nist.gov/node/1135216

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Smart manufacturing systems (SMSs) are envisioned to contain highly automated and IT-driven production systems. To address the complexity that arises in such systems, a standard and holistic model for describing its activities and their interrelationships is needed. This paper introduces a factory design and improvement (FDI) activity model and illustrates a case study of FDI in an electromechanical component factory. In essence, FDI is a reference activity model that encompasses a range of manufacturing system activities for designing and improving a factory during its initial development and also its operational phases. The FDI model shows not only the dependency between activities and manufacturing control levels but also the pieces of information and software functions each activity relies on. We envision that the availability of these pieces of information in digital form to integrate across the software functions will increase the agility of factory design and improvement projects. Therefore, our future work lies in contributing to standards for exchanging such information.

Key words: Activity model, Smart Manufacturing System, Factory Design and Improvement (FDI), Enterprise Integration, Reference Model

1. Introduction

A 2014 MESA report on a survey of manufacturers [33] found that the top performance criteria, which manufacturers across industries are using to make themselves more successful, are the ability to introduce new products and to deliver them on time. From the perspective of manufacturing operations, this ability to meet those performance criteria depends on several key capabilities. These capabilities include (1) quickly setting up or adapting production facilities for new products and product variations; (2) identifying the data needed to optimise operational effectiveness; and (3) providing accurate time estimates for production.

We are developing a model of the activities and systems involved in setting up new factories and improving or modifying existing factories for the purposes of improving performance or adapting the factory for the introduction of a new or variation of product. This model will help manufactures throughout the entire life cycle from planning to operation. Using the model, planning for new product introductions will be better orchestrated. Data to be collected to help in the decision-making throughout the activities will be clearly defined and analysed. Systems to use for collecting data along with standards will be more readily available so that the activities can be executed efficiently within and across organisations.

Since the dawn of the industrial revolution, setting up factories and planning for their improvements have been practiced; however, access to new technologies is allowing manufacturers to radically improve these activities. New technologies range from sensors to acquire more and better data on factory operations to advanced software capabilities to visualise and simulate operations. Proper connectivity and orchestration with the factory design and improvement activities are necessary to achieve efficiencies intended by implementing the technological advancements, resulting in smart manufacturing systems (SMS).

Our model highlights the interrelationships of implemented technologies in the context of a standard enterprise control hierarchy based on the ANSI/88 physical model [1]. In addition, the FDI model can provide an indication as to where additional sensors or software tools might be deployed and what data should be gathered. Note that other aspects of a manufacturing enterprise including product development and design and operational control are beyond the scope of this model. Activities related to physical construction of the factory are also not covered.

This paper describes the FDI reference activity model, using IDEF0 [26]. IDEF0 is a functional modelling methodology that can represent activities and their relationships in a hierarchical series (see the beginning of Section 4 for a description of IDEF0). Figure 1 illustrates the scope of the activities. The external inputs to FDI include:

- Product Information --products to be produced
- Market Information –product demands considering market condition
- Resource Information --resources required for producing the products and statuses of those resources

Much, if not all, of this information may be managed and supplied by manufacturing software systems, such as Digital Manufacturing (DM) [17; 18], Product Lifecycle Management (PLM) [40], Enterprise Resource Planning (ERP) [38], Supply Chain Management (SCM) [37] and the Manufacturing Execution System (MES) [22].

[Insert Figure 1 here.]

The rest of the paper is organised as follows. Section 2 reviews similar models in the area of manufacturing system operation management, in addition to extensive experience and studies that document all of the control decisions applicable to many types of manufacturing systems. FDI's essential principles are derived from these similar models. Section 3 describes the FDI activity model and modelling approach. The FDI activity model is based on a comprehensive study and years of industrial experience. It documents all of the design and control decisions in any manufacturing system [12; 16] and has been informed by similar research and the models described in Section 2. Section 4 illustrates the use of the FDI model and Section 5 provides conclusions and future directions.

2. Related Work

This section reviews relevant architectures, standards, processes and reference activity models used in developing the FDI activity model. The Systems Integration for Manufacturing Applications (SIMA) Reference Architecture [5] is a reference model for product realisation activities within a manufacturing enterprise. Supply Chain Operations Reference (SCOR) Model [4] is a reference process model for supply chain management. ANSI/88 Batch Control [1], ANSI/ISA95 Enterprise Control System Integration [2; 3] and the MESA Model [32] are models for enterprise controls. FPL (FPL-Fabriks Projkterings Lotsen, Factory planning and realisation process in English) [7] is a factory design process developed for part manufacturing. In this section, we analyse these related pieces of work and describe the unique value the FDI model provides. Subsection 2.1 provides a broad analysis of the work, while Subsection 2.2 provides detail analysis between the FDI model and SIMA architecture.

2.1 High-level Analysis of the Enterprise Models

Enterprise model development started in the early 1980s. Chen et al. performed a series of analyses and found that there was an absence of a scientific method to (1) validate an enterprise model proposal and (2) evaluate and compare different models [8]. In 1999, the IFIP/IFAC Task Force1 evaluated several enterprise models and concluded that no single model subsumed all others, even though there were many overlaps [6]. A qualitative analysis approach similar to that of Shin and Cho [39] is used; however, more detailed characterisation of each criterion is provided here. Table 1 shows the three qualitative criteria identified – synchronisation, coordination and formality. Table 2(a) indicates where each enterprise model addresses synchronisation within and across those life cycle phases. The IFIP/IFAC Task Force defined the Generalised Enterprise Reference Architecture and Methodology (GERAM) [6] which is used in the table for the different phases of the production system life cycle. The ISA 95 and MESA models only address a single phase (operation), whereas other models address multiple life cycle phases, with SCOR and FDI having the broadest coverage.

We use the nine GERAM phases to characterise the synchronisation ability of the model. The identification phase establishes the relations between the enterprise or any part of it, and its internal or external environmental factors. The concept phase develops the concepts (i.e. objectives) to be delivered, such as management vision, mission, value and operational concepts.

The requirement phase identifies the functional, behavioural, informational and capability requirements for the concepts. The design phase specifies the operational system with all it components meeting the identified requirements. The implementation phase develops the designed system. This phase is constrained by enterprise preferences or availability of technology and components. The build phase realises the system and includes the physical deployment of resources, testing and validation for design and operation of the system. Alternative component specifications for future improvements may be identified during the operation phase. The system change/re-engineering phase modifies the system to account for newly identified needs or to improve performances that may result in a deployment of new technologies. The end of life phase is concerned with the recycling or disposal of the system or components at the end of use.
The coordination criterion evaluates the vertical coverage of the model from the perspective of an enterprise control system. We use the control levels defined in the ISA-88 enterprise control hierarchy to describe the coordination criteria. The light grey indicates that the enterprise and the site may be collapsed into one control level. The seven enterprise control levels shown in Table 2(b) are explained in more detail in Table 4. They represent the sphere of influence for the model to coordinate activities and stakeholders across these control levels. As can be seen in the table, FDI has the broadest coordination across control levels, whereas the SCOR and ISA models are limited to the higher levels of control and the MESA, SIMA and FPL models address the middle areas of control. FDI is the only model that addresses control at the lowest levels.
Lastly, the Formality criterion reflects the type of information formally captured by the model. More coverage implies better usability of the model. The modelling features that we use for evaluating the formality of a model include the representation of

- activities and relationships between activities
- performance metrics
- relationships between an activity and the control architecture
- inputs, outputs, controls and mechanisms for each activity (the four flows represented in IDEF0).

Table 2c shows the analysis for Formality for each of the models.

[Insert Table 1 here.]

[Insert Table 2 here.]

Key observations from our analysis are as follows:

- None of the models capture activities across the whole life cycle and all control levels of a manufacturing system
- FDI and SIMA models are the most formal, and both use IDEF0. FPL uses a derivative of IDEF0; the other models do not use a formal approach.
- Although SCOR, SIMA, FPL and FDI synchronise similar stages of the life cycle, they focus on coordination in different parts of the enterprise. SIMA, FPL and FDI focus on the coordination within the factory (as indicated by the dark grey highlighting the control levels from the Area down to Control module), while SCOR focuses on the coordination of the supply chain. More specifically, FDI ensures that decision parameters from the enterprise and site are taken into account within the factory, but does not capture design and control activities at the enterprise and site levels.

- ISA 88 and 95 focus on describing activities and information associated in the operation phase only.

While the SIMA model has more activities than the FDI model, it covers aspects other than the life cycle of a production system, including product design. FDI provides additional detail to the SIMA model in the area of production. A detailed analysis between SIMA and FDI is provided in the next section.

2.2 SIMA-FDI Analysis

SIMA is the most comparable model to the FDI activity model since the scopes of the two models largely overlap, as shown in Table 2. Both models describe activities for production systems' engineering and both models are represented in IDEF0.

The SIMA Reference Architecture was developed by NIST in the late 1990s. Its major purpose was to provide a frame of reference for identifying and standardising the interfaces between software supporting product designs and manufacturing operations. It defines a set of activities, information flows and resources associated with the engineering and operational aspects of manufacturing a product from conception through production. The FDI activity model is based on industrial practices for factory design and operational improvements as described in [12; 16]. The two activity models nevertheless relate and overlap as highlighted below.

SIMA's level-1 activities include A1: Design Product, A2: Engineer Manufacture of Product, A3: Engineer Production System, A4: Produce Product and A5: Manage Engineering Workflow. The FDI activity model subsumes A2 and A3. Since the FDI activity model focuses on the design of a manufacturing system, it does not include any activities associated with A1. The FDI activity model, however, does use the outputs of A1 as inputs to the other activities. Similarly, A4 is about operating a factory. FDI focuses on activities which determine how to operate the factory.

FDI executes A4 activities during its Test phase (also A4 of the FDI model). Although we regard A4 as not covered by the FDI model, the outputs of A4 of the FDI model can be used as inputs to A4 of the SIMA model. A5 is excluded from the analysis because it was not fully developed in SIMA. Table 3 provides detailed mappings between the SIMA's A2 and A3 and the FDI's activities.

[Insert Table 3 here.]

Although A2 and A3 in the SIMA model are applicable to both factory development and improvement, they are limited to the product realisation perspective. The FDI model provides more refined activities from the perspective of factory performance management. Manufacturing system engineers whose daily job is concerned with improving system performance should find the FDI model satisfying their particular niche.

3. FDI Activity Model

This section presents a detailed FDI activity model. FDI uses IDEF0 representation, and it is also uniquely overlaid on the ISA-88 control architecture. Therefore, semantics of the fundamental IDEF0 elements and ISA-88 control architecture are described first.

3.1 Overview of IDEF0

IDEF0 is one of the activity modelling methodologies that is popular in academia, private industry and government [9; 24; 44]. An IDEF0 model is composed of diagrams in a hierarchical series with details describing the activities and interfaces among the activities within the specified boundary of a system. Each activity takes certain inputs and, by means of various mechanisms, transforms those inputs into a set of outputs subject to certain controls. The outputs from one activity are usually inputs to one-to-many other activities. These ICOMs (inputs, controls, outputs and mechanisms) are used to relate the activities. The relationships neither constrain nor imply a particular order among activities. The result is that IDEF0 is ideal as an instrument for developing a generic FDI, which can be customised for any specific domain. IDEF0 describes the activities of the system at different levels of abstraction and aggregation. The hierarchy of diagrams is based on a functional decomposition where each activity in a given diagram can be decomposed and represented in another, lower level diagram. The numbering in the lower right corner of the activity box represents the decomposition relationship. Figure 2 shows the basic IDEF0 representation with its four components--ICOMs overlaid on the FDI's A0 activity.

[Insert Figure 2 here.]

Inputs include all of the external data needed to perform the functions associated with the activity. Controls constrain the execution of the activity; for example, maximum time to complete the activity. Since these constraints can change over time, controls can change over time. Outputs can become either inputs or controls to other activities. These three arrows – input, control and output – are called information flows. Mechanisms determine how those flows take place; for example, supporting manufacturing software system or procedures.

Using the IDEF0 conventions, both activities and information flows are decomposable. At lower levels of abstraction, inherited ICOM identifiers are shown with each information object and mechanism. This piece of identifier information implies that a certain input may be a control to an activity at lower levels. Information flows can be bundled and classified as one of the three types: Type-Of, Part-Of or Undefined.

The mechanism of the proposed FDI activity model represents the mapping between the manufacturing software system and the activities. The mapping is important in formalising and identifying the opportunity for automating both the design and the implementation of SMS. When cross-referencing with the inputs and outputs, the mapping identifies information flows and interactions between these manufacturing software systems. As FDI's activities are also overlaid on the enterprise control architecture as specified by the ISA-88 standard [1], we turn to that next.

3.2 Overview of the ISA-88 control architecture

ANSI/ISA88 was developed originally for batch process manufacturing; however, its seven-level control architecture is applicable to other types of manufacturing. These seven control levels are summarised in Table 4. Business-oriented alternative names of these control levels are provided in the FDI Control Level's column. The Interpretation column provides a description. The keywords 'may' and 'must' convey the optional and required relationships to distinguish between levels, as typically small- and medium-sized enterprises may not have the site control level [42]. Mapping to the enterprise control levels is done at the sub-activity/task level. Some tasks may appear similar, but they are executed at different control levels. The level of abstraction of the activity model is designed to support analysis that is independent of domain and industry. For example, the FDI activity model does not further decompose the activity for different production types because the activities to verify process throughput vary depending on production types such as discrete and continuous. Additional decompositions could be added for given situations.

[Insert Table 4 here.]

3.3 The activity model

This section describes level-1 activities and sub-activities (also called tasks) including 'Develop Factory Requirement', 'Develop Basic Design', 'Develop Detailed Design' and 'Test'. These 28 tasks were identified from extensive experience of the industry experts in the electronics industry [12; 13; 14; 16]. While these tasks are identified to be ones that are performed regularly by electronics manufacturers (where both discrete and batch production types are frequently collocated), they are also highly pertinent to other manufacturing industries. Also, formally modelling them in IDEF0 will make dissemination of the knowledge contained in the activity model more accessible. The FDI activity model as a reference model provides a meaningful structure in which both industry and academia can develop cross-industry consensus. Figure 3 shows the level-1 IDEF0 diagram.

[Insert Figure 3 here.]

Note that the activities A2 Develop Basic Design and A3 Develop Detailed Design have sub-activities: A25, A27 and A37, that are associated with the layout design case described above. Also the sub-activities A21, A22, A23 and A26 of A2 Develop Basic Design can be associated with the capacity analysis case. These associations are the basis for smart, data-driven, improvements to the current practice.

3.3.1 A1 Develop Factory Requirement

'Develop Factory Requirement' is an activity to transform product information into factory requirements. Figure 4 provides an IDEF0 model for the 'Develop Factory Requirement' activity. Product information includes information about one or more products to be manufactured. To derive factory requirements, various types of information need to be taken into account such as existing resources, budget, time and administrative information. Factory requirements must be built to satisfy all the constraints suggested by the information and also to efficiently meet the product demands. Such factory requirements satisfying all the constraints identified in A1 are used to drive other activities including A2, A3 and A4 in various manners.

The A1 activity can be applied to develop an entirely new factory or to an improvement in an existing factory, such as adding a new production line, or reengineering an existing factory or production line to adapt to changing products, processes and performance requirements. The same set of activities in the FDI model may be performed slightly differently in the various situations of a new product introduction. For example, when new location candidates are available, A12 addresses alternatives for new factory development. Otherwise, A12 addresses only engineering or enhancing an existing factory. All other activities are similar in this respect. In other words, they may be performed differently for design or improvement activities.

[Insert Figure 4 here.]

A11 Analyse Market
The first sub-activity for A1 is to analyse the market. Future market trends are forecasted (e.g. larger screen smart phones; or ceiling mounted air conditioners).
Output: Market Analysis
Control levels: Enterprise ~ Area

A12 Analyse Infrastructure
Candidate infrastructures – including location, environment and regulations – are evaluated. The evaluations may include a high-level, rough-cut, cost–benefit analysis. Infrastructure analysis is one of the most important activities since infrastructure is difficult and expensive to change. These are long-term decisions that must be designed for uncertainty in the future environment. Factors that affect the infrastructure's location are cost, available business services, labour and other government regulations, labour availability, customer/market proximity, suppliers and competitors [41]. There are various methods to conduct the evaluation of location alternatives including The Factor-Rating Method, Locational Break-Even Analysis, Centreof-Gravity Method and the Transportation Method [30].
Output: Factory Locations
Control levels: Enterprise ~ Area

A13 Analyse Sales & Production Plan
Sales plans are equivalent to demand forecasts. Sales plans are established based on the market analysis from A11. Production plans are long-term capacity requirements to meet those demands. In establishing production plans, resources from existing factories that are compatible with products in the market analysis are used as a basis.
Output: Sales & Production Plans
Control levels: Enterprise ~ Area

A14 Assemble Factory Requirement
A factory requirement is developed that includes required budget, human resources, building and landscape construction schedule that meet the outputs from prior activities. At this stage, the exterior factory construction can be started according to the factory requirement.
Output: Required Human Resources, Required Building & Landscape Construction Schedule, Required Budget
Control levels: Enterprise ~ Area

3.3.2 A2 Develop Basic Design

The factory requirement identified in A1 is used in design activities to create factory specifications. The design activities are decomposed into two phases: 'Develop Basic Design' described in this section and 'Develop Detailed Design' described in the next section. In essence, 'Develop Basic Design' and 'Develop Detailed Design' are similar activities, but their outputs differ in the level of details. The purpose of the decomposition is to make available some aggregate design parameters early during the basic design where for other design decisions it takes longer to obtain more accurate design parameters from the detailed design. (See Section 4.1 for further discussion) Figure 5 provides an IDEF0 model for the 'Develop Basic Design' activity.

[Insert Figure 5 here.]

A21 Set Production Target
Each business unit determines production volumes for each product to meet the production plans (e.g. 200k iPhone 4; 300k iPhone 5; 500k iPhone 6 per year). Production type for each product and components are also determined. Production types can be continuous, intermittent, repetitive and project [30].
Output: Target Production Volumes
Control levels: Area ~ Unit

A22 Determine Equipment & Manpower Capacity
Necessary equipment types, their capacities and labour are estimated to satisfy the target production volumes [10; 11]. In this stage, information from existing factories can be used as references. Manufacturing layout type for each product also influences the required capacities. Manufacturing layout types can be, for example, product-based layout, process-based layout, fixed location layout, cell layout and U-type layout, among others [29].
Output: Resource Capacity Requirements
Control levels: Process cell ~ Unit

A23 Verify Process Throughput
The throughput of each process in the cells or lines is verified to meet the estimated resource capacity requirements.
Output: Process Throughput Verification
Control levels: Process cell ~ Unit

A24 Set Lot Size
Proper lot sizes have to be calculated with balance among inventory costs, production lead times and set-up and handling costs. Inventory costs and production lead times are lower proportionally with the lot size; however, setup and handling costs have inverse relations with the lot size. The relationships between inventory costs and production lead times are analysed to set lot sizes in order to minimise the total operating cost.
Output: Lot Sizes
Control levels: Process cell ~ Unit

A25 Design Auxiliary Facility
Additional facilities not directly related to the manufacturing, such as dressing room, restroom and break room, are designed. Some of these facilities are necessary because they are required by laws governing a safe working environment.
Output: Auxiliary Facilities Layout
Control levels: Area ~ Unit

A26 Design & Verify Manufacturing Line
Processes, equipment, buffer and inventory in each manufacturing line (or cell) are located. Each line is then individually verified for efficient flows and throughputs with respect to lot sizes, input docks, output docks and storage.
Output: Manufacturing Lines Layout
Control levels: Area ~ Process cell

A27 Assemble Basic Factory Layout
This activity combines the outputs from A25 and A26 to optimise the layout of the lines or cells for both production efficiency and space. The basic factory layout concerns are primarily with processing equipment. Material-handling equipment is considered in A3. The layout of the whole factory is verified in detail with respect to the factory requirements (output from A1). This comprehensive verification can discover a number of errors and conflicts because in this state, all feasible lines are considered simultaneously. The verification should also aim to reduce space usage. This not only improves productivity per square feet, a key performance indicator, but also can reduce material-handling time and cost. Therefore, activities A23 to 27 are typically carried out repeatedly to resolve these errors and conflicts.
Output: Verified Basic Factory Layout
Control levels: Area ~ Process cell

A28 Develop Production Management System
After all physical elements related to the factory are specified, a production management system for factory operation is designed. Generally, a production management system is an MES (manufacturing execution system). Information and functional requirements for the production management system are gathered. Plans for development of the production management software are developed.
Output: Production Management System Specification
Control levels: Area ~ Control module

A29 Assemble Basic Factory Specification
In this last activity, all outputs from the previous activities are put together and reviewed for consistency with the enterprise-level data and objectives (e.g. comparing the current design with existing factory designs). An important part of the basic factory specification is the cost estimation.
Output: Basic Factory Specification
Control levels: Enterprise ~ Unit

3.3.3 A3 Develop Detailed Design

'Develop Detailed Design' is an activity to refine the basic factory specification from A2 into a detailed factory specification. Actual realisation of the factory interior also begins in this activity. Figure 6 provides an IDEF0 model for the 'Develop Detailed Design' activity.

[Insert Figure 6 here.]

A31 Manage Capital Procurement
This activity analyses the relationships between the cost aspect of the designed factory and the basic factory specification from A2. Equipment and software for building up manufacturing lines and production management systems are procured. Their costs are managed in accordance with the estimated cost from A2.
Output: Capital Procurement Plan
Control levels: Enterprise ~ Area

A32 Determine Manufacturing Method & Technology
This activity develops new manufacturing methods and technologies needed to produce the desired products in the most efficient and effective way. This activity includes identifying stock materials, components to be used and sequence of the major processes to be performed. If a particular manufacturing method and technology are totally new, it is necessary to develop them. Consequently, specifications for the necessary tooling need to be identified along with instructions for use and maintenance information. Lastly, a new method or technology may require restructuring of information to be used for production. This activity applies only to the case where a new manufacturing process is required. It is also important for continuous improvement of the factory.
Output: Manufacturing Methods & Technologies
Control levels: Unit ~ Control module

A33 Design Production Equipment
This activity determines the specification of new equipment with respect to the new manufacturing methods and technologies from A32. A procurement plan for equipment that meets such specification must also be established. In addition, a maintenance plan for the procured equipment is developed. Any change in equipment specification needs to be reflected in A28 (Develop Production Management System) since the data to be gathered for the production management system also need to be updated.
Output: Production Equipment Specifications & Development Plans
Control levels: Equipment module ~ Control module

A34 Design Inspection Equipment
This activity is similar to the previous activity A33, but focuses on the development of a new measurement and inspection equipment.
Output: Inspection Equipment Specifications & Development Plans
Control levels: Equipment module ~ Control module

A35 Design Material Flow
This activity develops a material flow specification based on detailed specification of all production and inspection equipment determined from the previous activities. These details are incorporated into the layout design in the A2. Within this design activity, a detailed material flow analysis for the whole factory is carried out to verify the material flow specification. Material flows can be analysed between floors, manufacturing lines and processes within a factory.
Output: Material Flow Requirement
Control levels: Area ~ Unit

A36 Design Material Handling System
This activity designs material-handling systems to meet the material flow requirement. Material-handling systems are sets of equipment to transport parts across factory. The efficiency of the material-handling systems greatly affects the overall performance of manufacturing system. Plans for development and/or procurement of the material-handling systems are developed.
Output: Material Handling System Specifications & Development Plans
Control levels: Area ~ Unit

A37 Design Factory Layout
This activity incorporates the material-handling system's details into the layout design. This completes the details of the factory layout design. A complete verification should be performed with respect to the required performance criteria. Similar to A27, this activity can discover a number of conflicts because all elements designed for a factory are simultaneously considered.
Output: Detailed Factory Layout
Control levels: Area ~ Unit

A38 Develop Material Management Plan
This activity finalises inventory management plans such as just-in-time delivery, order quantities or vendor-managed inventory. Procurement plans including supplier selections and logistic supports for direct and indirect materials are established.
Output: Material Management Plan
Control levels: Enterprise ~ Unit

A39 Assemble Detailed Factory Specification
This activity reviews and finalises all elements designed from the prior activities. After this detailed design review, all elements will be developed and installed.
Output: Detailed Factory Specification
Control levels: Enterprise ~ Control module

3.3.4 A4 Test

'Test' is an activity to initialise and commission the designed factory, to optimise for performance, given changing product demands and manufacturing variability, and to develop plans to respond to disturbances and disruptions. Figure 7 provides an IDEF0 model for the Test activity.

[Insert Figure 7 here.]

A41 Verify Production & Inspection Equipment
This activity tests and adjusts individual production and inspection equipment that have been installed to meet the detailed factory specification. In addition, their connectivity to the production management system (MES) for data collection is verified.
Output: Equipment Verification Result
Control levels: Equipment module ~ Control module

A42 Verify Process

This activity tests and adjusts unit processes that compose a manufacturing line. While A23 virtually verifies the throughput of each process against the estimated resource capacity requirements, this activity performs a physical verification of each process to determine if it meets the detailed factory specification.
Output: Process Verification Result
Control levels: Process cell ~ Unit

A43 Verify Material Handling System
This activity tests and adjusts individual material-handling systems that have been installed to meet the detailed factory specification. After all equipment are arranged, this activity checks to see if there are any clearance or reachability problems and if the material flow meets the detailed factory specification.
Output: Material Handling Systems Verification Result
Control levels: Area ~ Equipment module

A44 Verify Factory Layout & Material Flow
This activity verifies factory layout to ensure that all equipment are located at the right locations according to the design. Then material flow within each manufacturing line is verified to meet the detailed factory specification.
Output: Material Flow & Factory Layout Verification Result
Control levels: Area ~ Equipment module

A45 Test Factory
This activity conducts trial runs of the factory where all manufacturing lines are verified along with the production management system. Production performances are evaluated. Unexpected problems (i.e. emerging behaviours) may appear and have to be resolved. In addition, potential disturbances and disruptions to the production system are analysed and response plans are developed.
Output: Factory Testing Result, Corrective Action & Preventive Action Plans
Control levels: Area ~ Control module

A46 Standardize Factory
This activity establishes standard operating procedures (SOP) from the factory testing result.
Output: Standard Operating Procedures (SOP), New or Updated Factory Specification
Control levels: Enterprise ~ Control module

4. A case study

This section describes a case study which demonstrates the application of the reference FDI activity model. This study was conducted in an electromechanical component factory [12; 16]. A number of studies have found that model-based engineering avails an organisation of multiple stakeholders to perform activities concurrently and cooperatively [19; 20; 25; 27; 34; 35; 36]. We show that the FDI activity model also promotes such coordination and improves performance. In the following subsections 4.1 and 4.2, the layout design and the capacity analysis problems are, respectively, used to illustrate the improvement resulting from following the FDI activities. Taking the FDI model further, subsection 4.3 shows the impact where an FDI-based system was developed and applied to digitise the layout design and capacity analysis.

4.1 Layout Design

Activities relevant to layout design in the FDI activity model include A27 (Assemble Basic Factory Layout) and A37 (Design Factory Layout).

Choi, Sung et al. [16] reported that 2D CAD models were used, in lieu of a detailed functional model, as a means to collaborate between different stakeholders including layout designers, manufacturing engineers, capacity analysts and general managers. Using these 2D CAD models, spatial constraints were identified to specify the location of all factory equipment in an attempt to minimise both the likelihood of interference and overall space usage. One major drawback in this approach was that the entire layout design was completed as one ongoing activity. This was a lengthy activity that could not be finished before the start of the facility construction. Therefore, construction was started with insufficient requirements necessitating reiterations of the activity to adjust for the actual constructed facility. It caused serious delays that affected the entire development of the factory.

In contrast, the FDI activity model proposes a two-staged approach for the layout design including the design basic factory layout and the design detailed factory layout activities. Figure 8 shows the difference in the levels of detail between the outputs from these two activities. In (a), the objective is to develop a draft factory layout rapidly to produce sufficient information in time for concurrent and subsequent analyses. For example, manufacturing areas are specified roughly based on prior knowledge of equipment specifications in (a), while detailed layout has to be completed with actual equipment designs and specifications in (b). This way, sufficient information is available to resolve potential conflicts during the facility design before actual construction resulting in reduction of reworks for the rest of activities (A2 to A4).

[Insert Figure 8 here.]

4.2 Capacity analysis

Activities relevant to capacity analysis in the FDI activity model include A22 (Determine Equipment and Manpower Capacity), A23 (Verify Process Throughput), A26 (Design and Verify Manufacturing Line).

In a typical new factory design or improvement activity, multiple capacity analyses need to be performed by multiple stakeholders at different levels in the manufacturing control hierarchy. Without a collaborative and holistic consideration of the interactions among these capacity analyses, stakeholders used incompatible methods and tools. In addition, these analyses were performed at inappropriate times. For example, the enterprise-level stakeholders used a method based on mathematical models that relied on rough estimates of equipment specifications, product quantities, resource utilisations and man-hours as inputs. When more accurate estimates became available from the lower levels, they were not fed back to the enterprise stakeholders so that they could refine their analysis.

In contrast, the FDI activity model specifies the dependency between different capacity analyses including A22, A23 and A26.

This orchestration results in more accurate and complete information being used by all stakeholders as it becomes available. For example, the output from the capacity analysis of an equipment and manpower activity (A22) is a part that constitutes the capacity analysis of a whole manufacturing line. Such information can be used for capacity analysis in A23 whose outputs should be subsequently used in A26. Using more accurate information, the FDI activity model produces better, coordinated capacity analysis' results than before.
Due to information interconnections between these activities, an integrated system based on the FDI activity model can be developed. This integrated system improves the efficiency of both factory designs and improvement processes by facilitating unified information flow and analysis methods used by different stakeholders, as is discussed in the next section.

4.3 Impact of applying the FDI-based system

The FDI activity model identifies pieces of information and their interconnections across the FDI activities and software tools (the mechanism in the model). In this section, we describe the impact of implementing an integrated software system based on the information flows in the FDI reference activity model, for the layout design and capacity analysis examples above. In the implementation, information schemas were developed based on the inputs, outputs and controls identified in the FDI activity model. These schemas [13] were used to integrate software tools and methods across the FDI activities. The deployment of the integrated system resulted in significant reductions in times required for a new factory development project and a factory improvement project. These reductions were calculated based on previous projects performed in other similar factories without the FDI-based system. In particular, the deployment in the electromechanical component factory resulted in the reduction of combined time to complete critical project activities, including layout design, manufacturing line design, capacity analysis and material flow analysis, from 6 to 1.5 weeks in the new factory development case and from 4 to 1 week in the factory improvement case [12]. A breakdown of how these improvements affected factory performance is summarised in Table 5.

[Insert Table 5 here.]

These improvements can be attributed to the followings:
(1) A unified database was available and information could be shared across stakeholders and activities in various stages.
(2) Unified software tools and methods for analysis activities were available with integrated and simplified user interfaces.
- (a) A unified analysis method was used for each type of analyses.
- (b) Accurate analysis' results could be obtained faster. In certain analyses, such as the capacity analysis, a single engineer could perform three related capacity analyses within a single streamlined user interface.
- (c) A unified, improved analysis result for each type of analyses was shared across stakeholders.

5. Conclusion and Future Work

In this paper, we formalised activities and their relationships in our reference Factory Design and Improvement (FDI) activity model using IDEF0, for designing new and for improving existing factories. In addition to the ICOMs identified in the IDEF0 model, ISA88-type control levels are identified for each activity. Employing a workflow based on the proposed activity model promotes orchestration of information and activities across various stakeholders at different control levels of the enterprise.

We envision that this can improve the decision-making process compared to a system where there is no clear factory design and improvement workflow. The information elements (inputs, outputs and controls) and software tools (mechanisms) identified in the activity model can be used to develop an FDI-based integrated software system. The FDI-based integrated system unifies different analytical methods and tools that would otherwise be disconnected across different stakeholders and tasks in the enterprise. This allows for analysis results to be obtained faster with more accuracy because up-to-date information is always available.

The FDI activity model provides the basis for identifying information requirements for unifying these viewpoints across manufacturing control levels. Until recently, such unification was difficult to achieve. The introduction of a variety of new technologies such as Information and Communications Technologies (ICT) into a manufacturing organisation is making it possible. As a result, we can start looking at the manufacturing enterprise more holistically, which is the essence of smart manufacturing.

This type of availability of information and advances in software technologies has resulted in 'model-based' disciplines in a number of fields including model-based engineering (MBE) of products, model-based systems engineering (MBSE) [23] and the building information model (BIM) [21] for capital facilities construction. All of these disciplines rely on a common standards-based structure for the model. The FDI activity model is the first step in formulating a model-based discipline for factory design and improvement. A preliminary study in formulating an information model based on the FDI activity model was done by developing a XML schema that consists of the P3R (Product, Process, Plant and Resource) information [13].

We have tested the applicability of the FDI activity model with industry partners though a use case. To further that, our future work will focus on (1) developing a coherent information model for integrating the FDI activities, (2) mapping the information model to identify gaps in existing standards [15] and (3) contributing to new standards to fill in those gaps. In addition, performance metrics can be constructed based on the activity model similar to the MESA study [31] and used to drive the performance management of the manufacturing operation.

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Tables

Table 1. Criteria for characterizing models

Criteria	Definition	Possible values
Synchronization	Synchronization is characterized based on coverage of the model across the lifecycle of an enterprise system [7].	Identification, Concept, Requirement, Design, Implementation, Build, Operation, System Change/Re-Engineering, End of life
Coordination	Coordination is characterized based on coverage of the model across the control levels [1**Error! Reference source not found.**].	Enterprise, Site, Area, Process Cell, Unit, Equipment Module, Control Module
Formality	Formality indicates the types of information formally represented in the model. Formality of the model is positively correlated with its reusability [43].	Activity, Input, Output, Control, Mechanism, and Relationships between them with respect to the IDEF0 model.

Table 2. Comparison charts among enterprise models

a) Synchronization

	Identification	Concept	Requirement	Design	Implementa-tion	Build	Operation	System Change	End-of-Life
SCOR									
ISA-88 & ISA-95									
MESA Model									
SIMA									
FPL									
FDI									

b) Coordination

	Enterprise	Site	Area	Process Cell	Unit	Equipment Module	Control Module
SCOR							
ISA-88 & ISA-95							
MESA Model							
SIMA							
FPL							
FDI							

c) Formality

	Activity	Between Activities	Performance Metrics	Between Activity & Control Architecture	Input	Output	Control	Mechanism
SCOR								
ISA-88 & ISA-95								
MESA Model								
SIMA								
FPL								
FDI								

Table 3. Mapping between SIMA's A2 and A3 and FDI activities

SIMA / FDI	A1	A2	A3	A4
A21 Determine Manufacturing Methods			V	
A22 Determine Manufacturing Sequences			V	
A23 Engineer New Processes			V	
A24 Develop Tooling Packages			V	
A25 Develop Equipment Instructions			V	
A26 Finalize Manufacturing Data Package			V	
A31 Define Production Engineering Problem	V			
A32 Specify Production & Support Processes		V	V	
A33 Design Production System		V	V	
A34 Model and Evaluate System	.		V	V
A35 Define Implementation Plan				V

Table 4. FDI control levels interpretation

ISA88 control levels	FDI control levels	Interpretation	Examples	Comments
Enterprise	Enterprise	A manufacturing enterprise may consist of one or more business units.	An electromechanical component manufacturing enterprise	A manufacturing enterprise may possess one or more business units. A business unit may manage one or more products or subassemblies. A factory must produce one or more products or subassemblies.
Site	Business unit, department	A business unit may consist of one or more factories.	Passive component division, PCB (Printed circuit board) division, Camera module division	
Area	Factory, plant	A factory must consist of one or more manufacturing lines.	Chip bead (type of passive component), Package substrate (type of PCB), ISM camera module (type of camera module)	
Process cell	Manufacturing line	A manufacturing line must consist of one or more manufacturing processes.	A manufacturing line that produces package substrate consisting of cutting, scrubbing, laminating and other manufacturing processes	A manufacturing line is defined as a set of manufacturing processes to deliver a final product or subassembly. Multiple manufacturing lines may share the same manufacturing process.
Unit	Manufacturing process	A manufacturing process must consist of one or more pieces of equipment and/or labor.	A manufacturing process of scrubbing that consists of equipment and labor	Scrubbing removes the oxide layer and dust off a PCB.
Equipment module	Equipment, labor	An equipment must consist of one or more equipment components.	A PCB scrubbing machine	A manufacturing process may be performed using specialized equipment or a set of generic purpose machines for the PCB surface treatment.
Control module	Equipment component	An equipment component is the lowest element in this functional breakdown of control levels	A brush (a component in the PCB scrubbing machine)	A brush may be used to remove any residual dust from the PCB scrubbing machine process.

Table 5. FDI-based system impact analysis [12, 16]

	Improvement of factory performance			**Reduction in project time**		
	Productivity index	**Cost index**	**Capacity index**	**Layout design**	**Material flow analysis**	**Capacity analysis**
New factory development	25%	25%	12%	55%	50%	35%
Existing factory improvement	20%	20%	9.2%	40%	45%	-

Figures

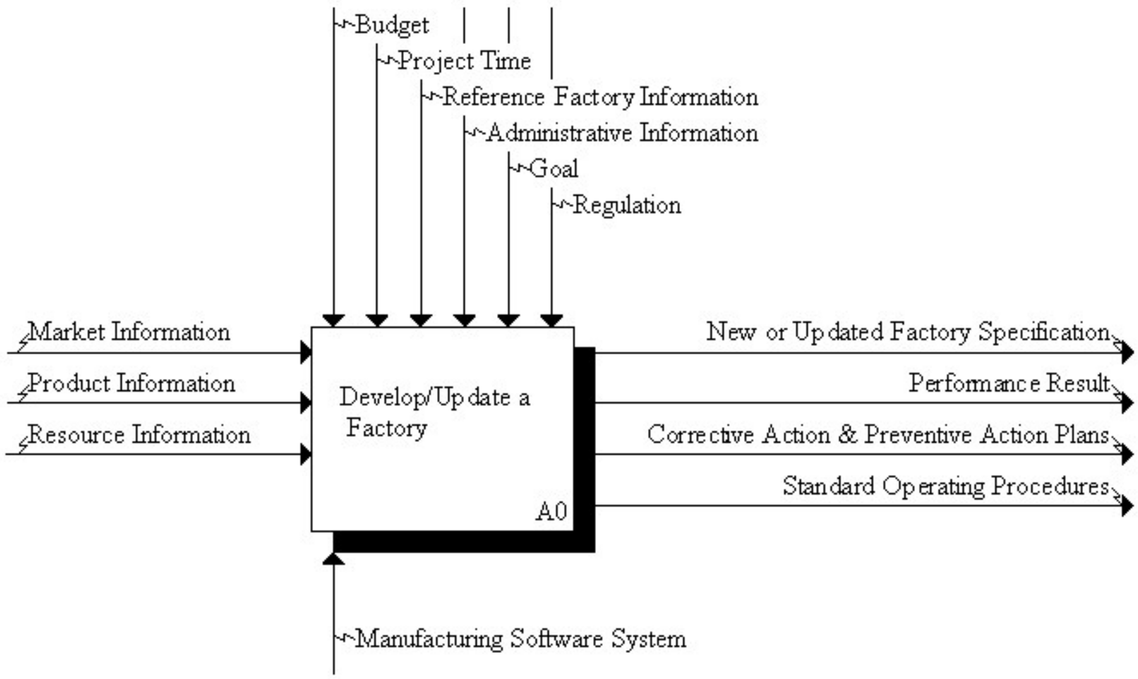


Figure 1. The top-level view of the FDI activity model [28]

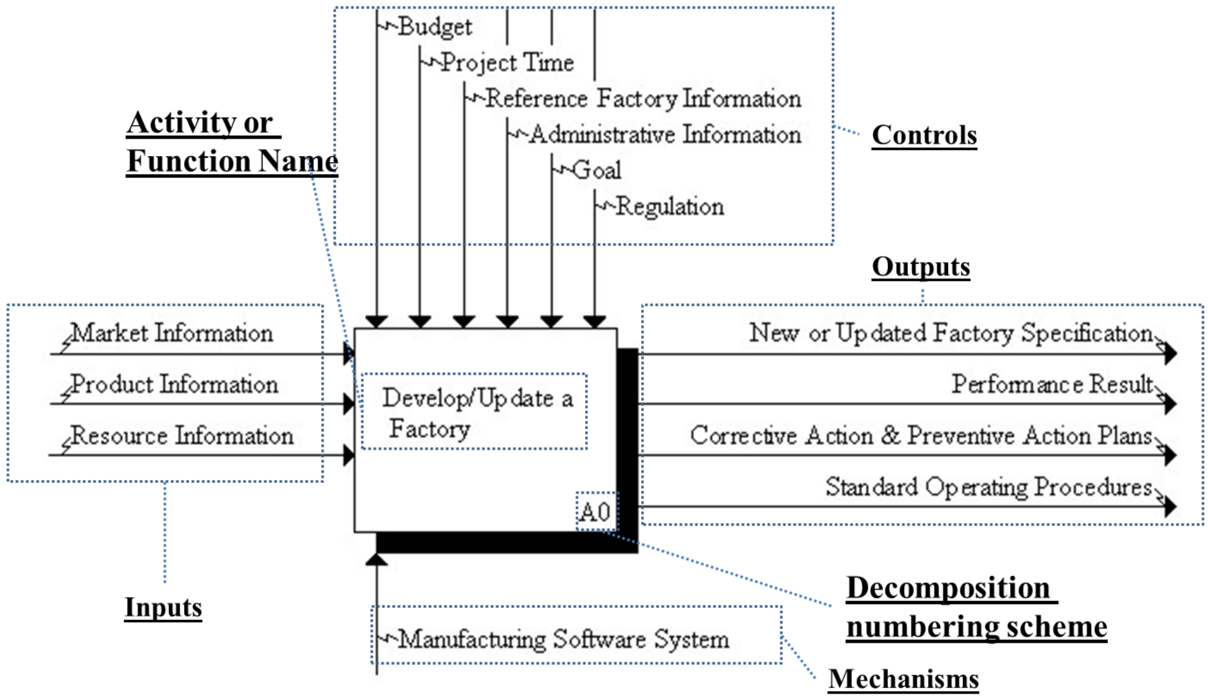


Figure 2. Basic IDEF0 representation of an activity overlaid on FDI's A0

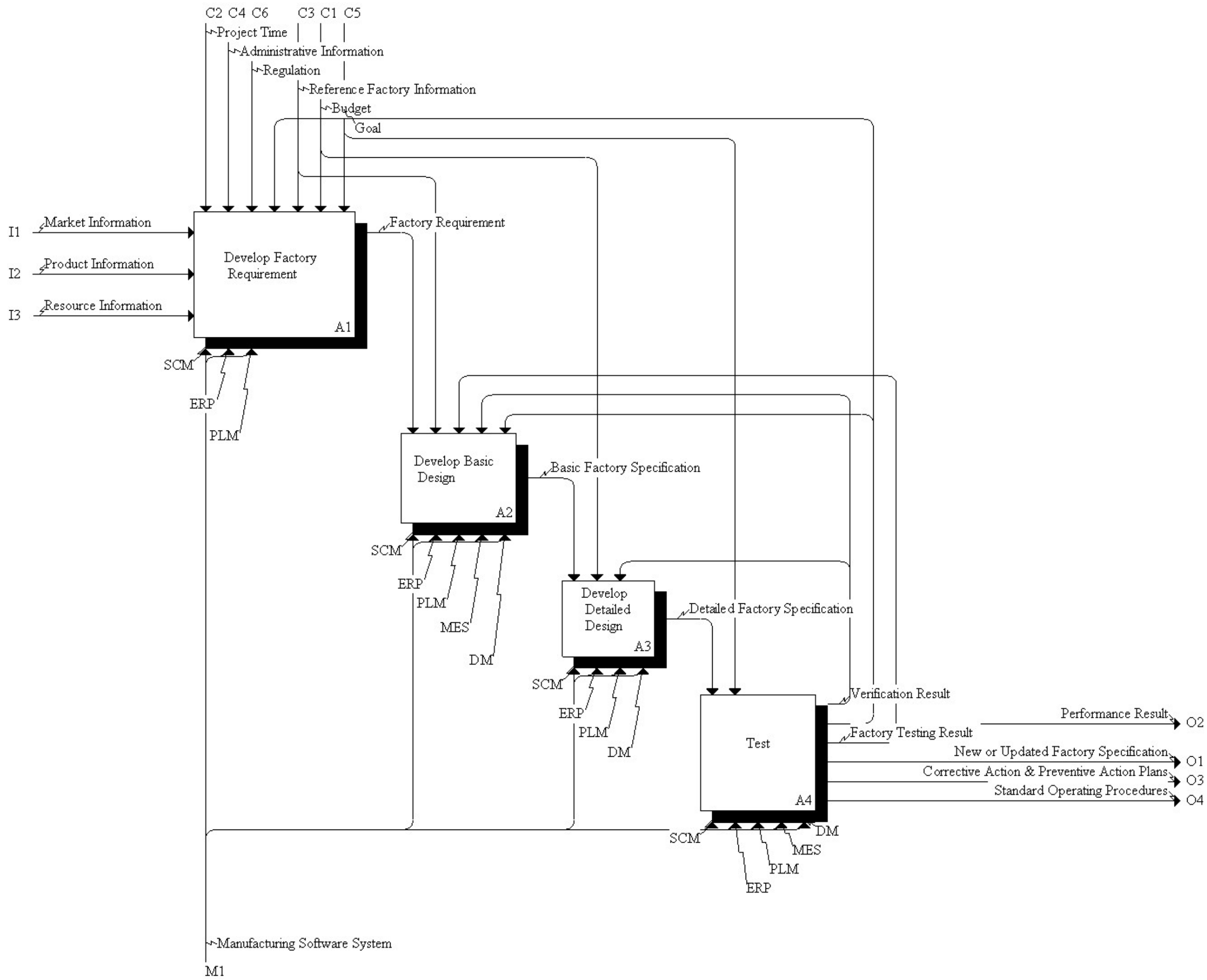


Figure 3. IDEF0 model of 'Develop/Update a Factory'

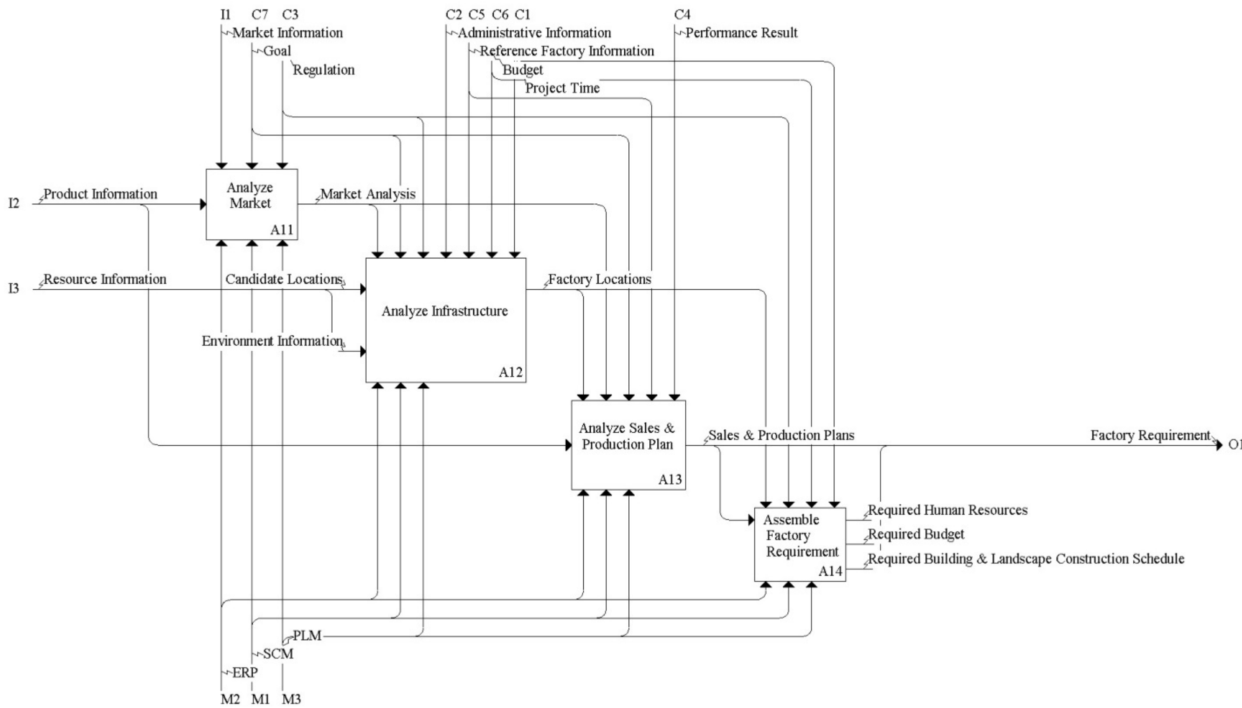


Figure 4. IDEF0 model of 'Develop Factory Requirement'

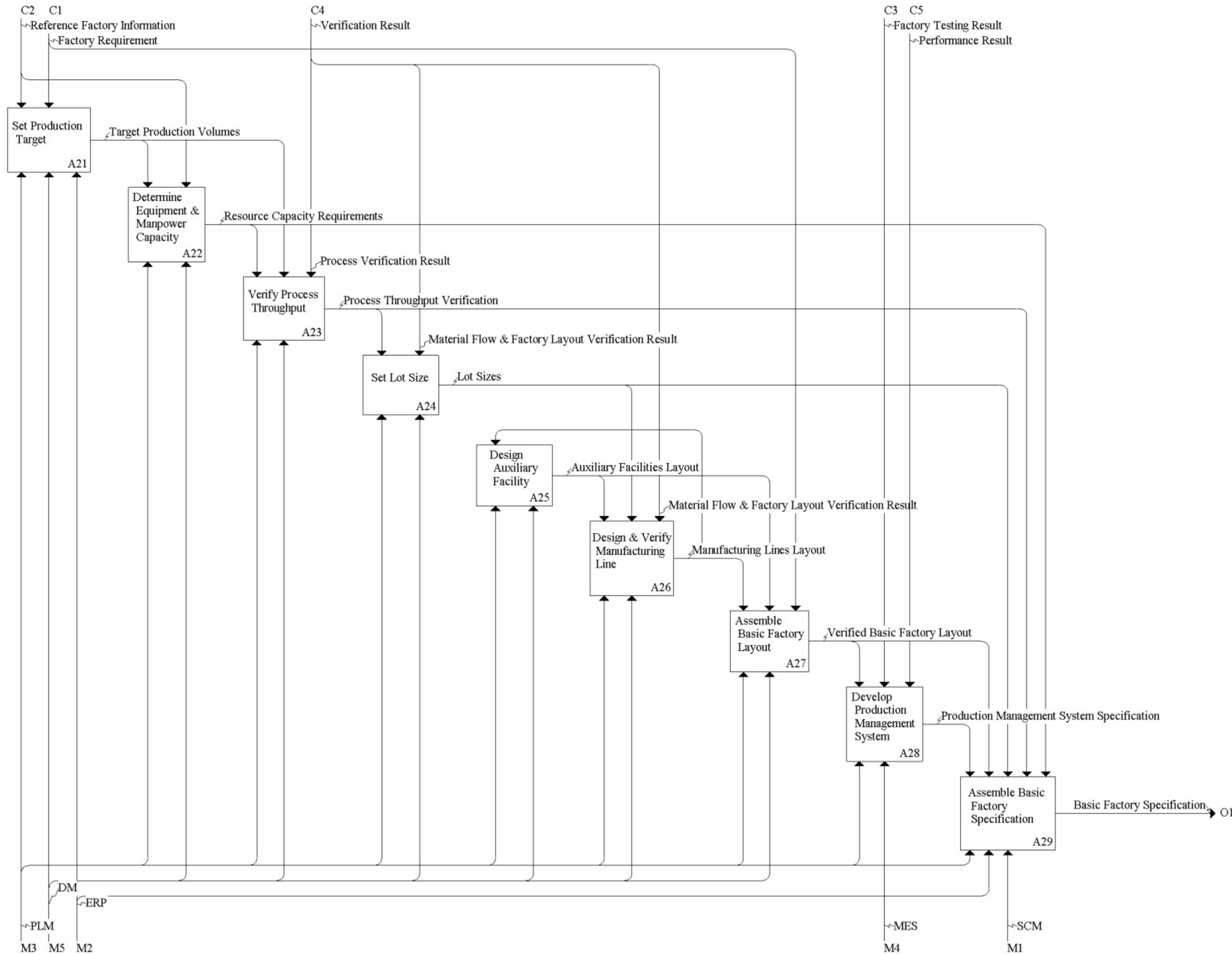


Figure 5. IDEF0 model of 'Develop Basic Design'

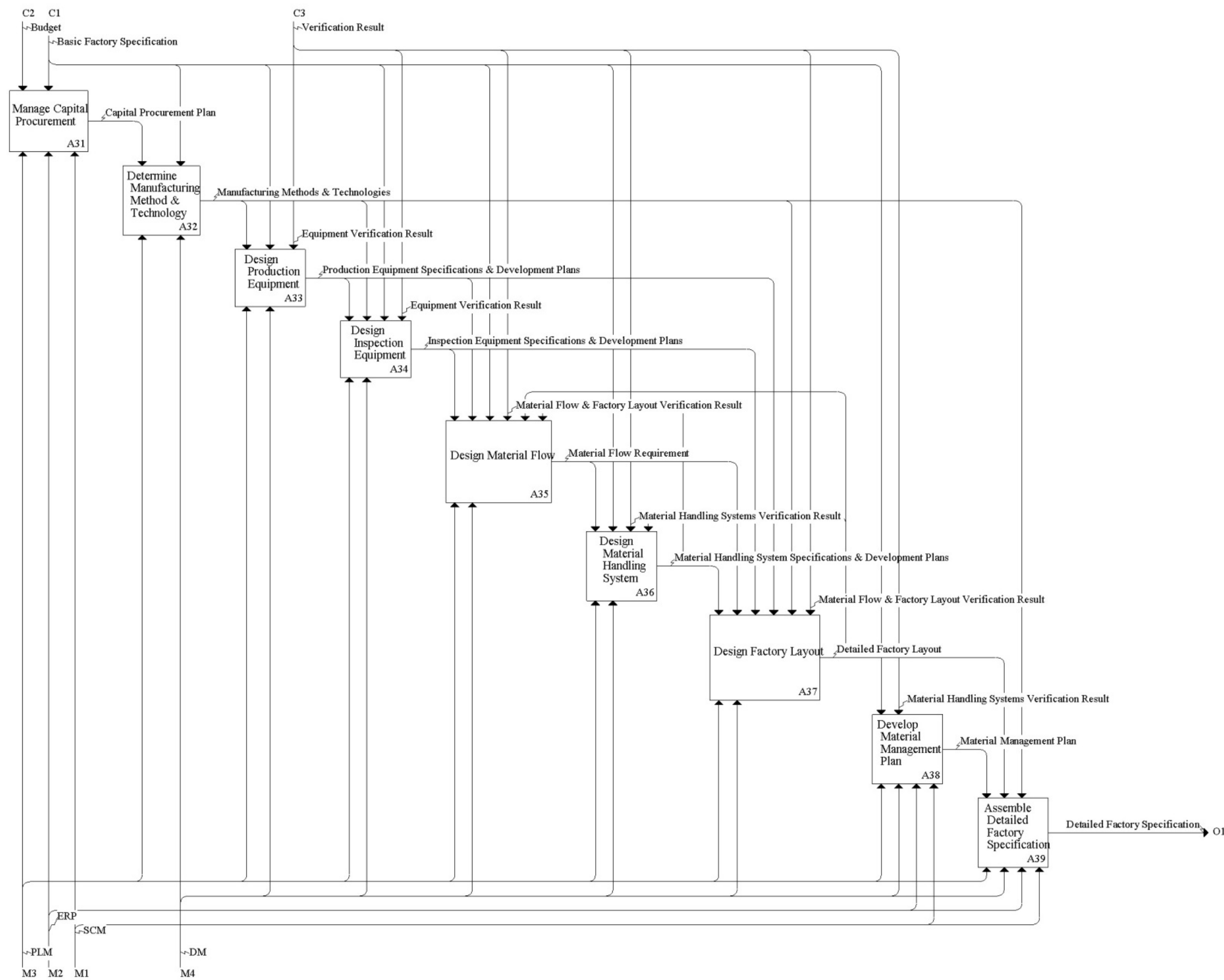


Figure 6. IDEF0 model of 'Develop Detailed Design'

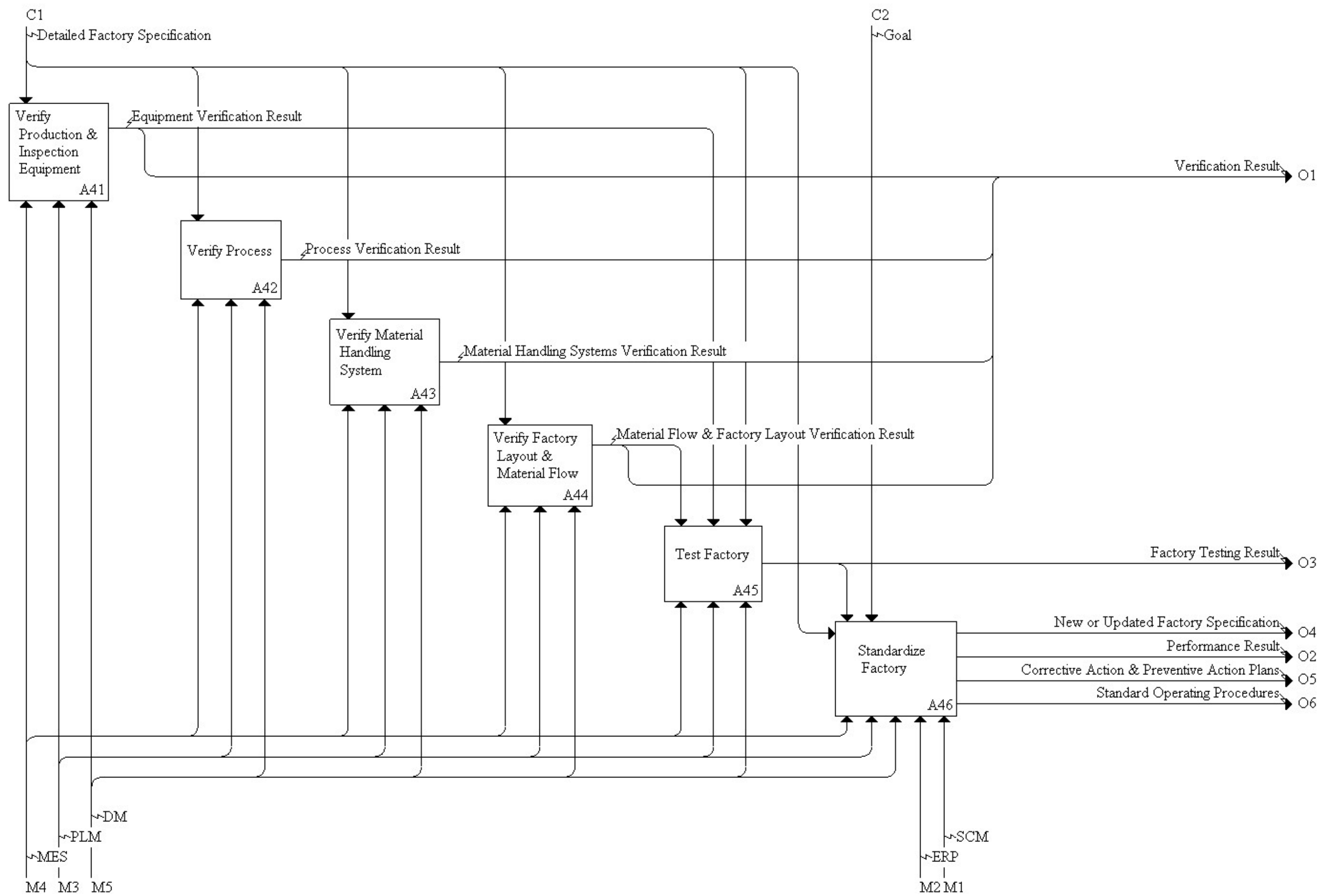
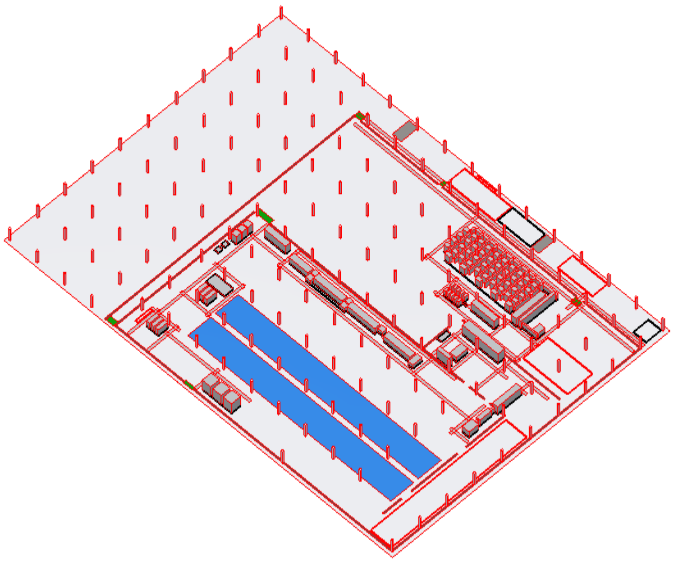
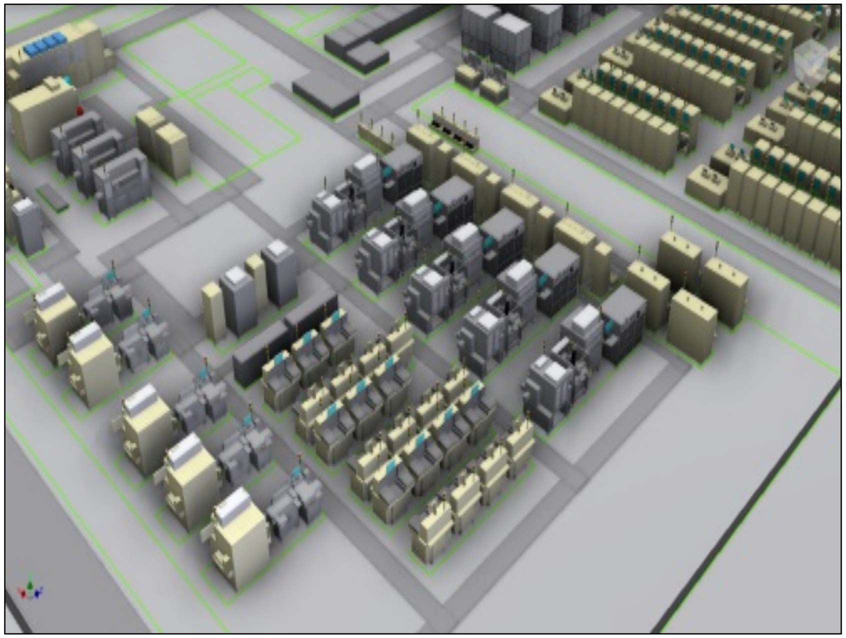


Figure 7. IDEF0 model of ‘Test’



(a) Design basic factory layout



(b) Design detailed factory layout

Figure 8. Illustrative factory layouts [12, 16]