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# Industrial automation systems and integration — Formal semantic models for the configuration of global production networks

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# National foreword

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The UK participation in its preparation was entrusted to Technical Committee AMT/4, Industrial data and manufacturing interfaces.

A list of organizations represented on this committee can be obtained on request to its committee manager.

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# Industrial automation systems and integration — Formal semantic models for the configuration of global production networks

*Systèmes d'automatisation industrielle et intégration — Modèles sémantiques formels pour la configuration des réseaux de production mondiaux*

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# Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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This document was prepared by Technical Committee ISO/TC 184, *Automation systems and integration*, Subcommittee SC 4, *Industrial data*.

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# Introduction

In reacting to change, competitive manufacturing industry aims to best understand the balance of possible options when making decisions on complex multi-faceted problems. Understanding how best to configure and re-configure a global production network, set against rapidly changing product-service requirements is one such complex problem area. Decisions consider multiple existing product and service variants, multiple new products and services to embrace the implications of new technological, economic, social, environmental and political requirements, and current production and service loads, as well as harmonizing and synchronizing production networks spread throughout the world, considering factors such as local supplier capabilities, transportation constraints, plant energy usage and production load forecasts.

While current Information and Communication Technology (ICT) tools play a significant role in support of such business development decisions, they need to do this in a well-integrated, trans-disciplinary way, with holistic solutions being critical to long-term competition (Huber 2014). Part of the solution to this problem lies in the exploitation of semantic technologies that provide a formal, logic base route to sharing meaning. This has been recognized as offering the potential to support interoperability across multiple related applications (Borgo et al. [23]; Chungoora et al. [24]). These provide formal, computer-based, methods of interpreting the meaning of concepts, their relationships to other concepts, and the constraints and rules that apply to their use.

The range of work in the use of formal semantics can be categorized into domain ontologies, foundation ontologies and reference ontologies. Domain ontologies tend to be limited to fairly narrow domains of applicability and so do not meet the holistic requirements mentioned above. Foundation ontologies are developed with a view to defining the semantics of everything but are too generic to offer positive constraints on any particular area of interest. The aim of reference ontologies for manufacture is to bridge the gap between these two and offer an effective support for interoperability, but in a targeted area or interest, i.e. in manufacturing. This document provides a contribution to such a manufacturing reference ontology by providing a formal semantic modelling approach to support the configuration of global production networks. It exploits the understanding gained from ISO 15531 and ISO 18629.

The manufacturing industry focus of this document is on how to design and configure a global production network (GPN) to produce and operate a new physical product or product-service. It does not address any operational aspects of production facilities, but rather models the flow relations between facilities in a production network. Future standards can build on this document to develop standard sematic models for in-factory systems.

The approach taken is based on exploiting the specialization capabilities of formal logic in order to progressively develop and constrain concepts and their relationships from foundation level descriptions to a level where the semantic models can be exploited by domain level software services and applications. The modelling approach starts from a systems functionality context as base from which to progressively represent global production systems, their relationships, constraints and related rules. The use of formal logic enables these semantic models to not only capture hierarchical relationships but also to capture and computationally exploit the constraints and rules that have been defined within these models.

The levels described in this document are different from the layered operational functionality of IEC 62264. The levels in this document are focused on levels of concept specialization. This starts from the key concepts from the context of any type of system through to specializations that are specific to manufacturing business systems. This is distinct from the layered operational functionality of IEC 62264, which is focused on the operational hierarchy of the business from higher-level production management down to shop floor.

This document uses some concepts that are common to supply chain models such as the Supply-Chain Operations Reference (SCOR) Model (Supply Chain Council 2014) and some concepts that follow from ISO 19440. SCOR is of limited relevance to this document as operational support is beyond its scope. Concepts from ISO 19440 have the greatest synergy with this document, which shares a business process oriented approach to enterprise modelling. While ISO 19440 provides model views to allow the identification of relevant object hierarchies and relationships between the different classes and

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subclasses, this document starts from a systems functionality context in order to build all subsequent hierarchies and relationships, including semantic constraints and rules.

This document is also distinct from the IEC/TR 62541 OPC Unified Architecture, although they both provide support to multi-vendor systems interoperability. IEC/TR 62541-1 provides a standard interface to facilitate the development of applications by multiple vendors that interoperate seamlessly together.

There are many semantic models that impinge on decision-making concerning the configuration and re-configuration of global production networks, as illustrated in Figure 1. This document provides the underpinning approach to the development of all of these models, but is necessarily focused on the production network concepts shown in Figure 1. Models of indicators, metrics, business, project, risk, location, scenario and product are therefore outside the scope of this document. The full value of this document can be gained through the development of future standards covering this full range of information, based on this document and drawing on existing standards in these areas wherever possible.

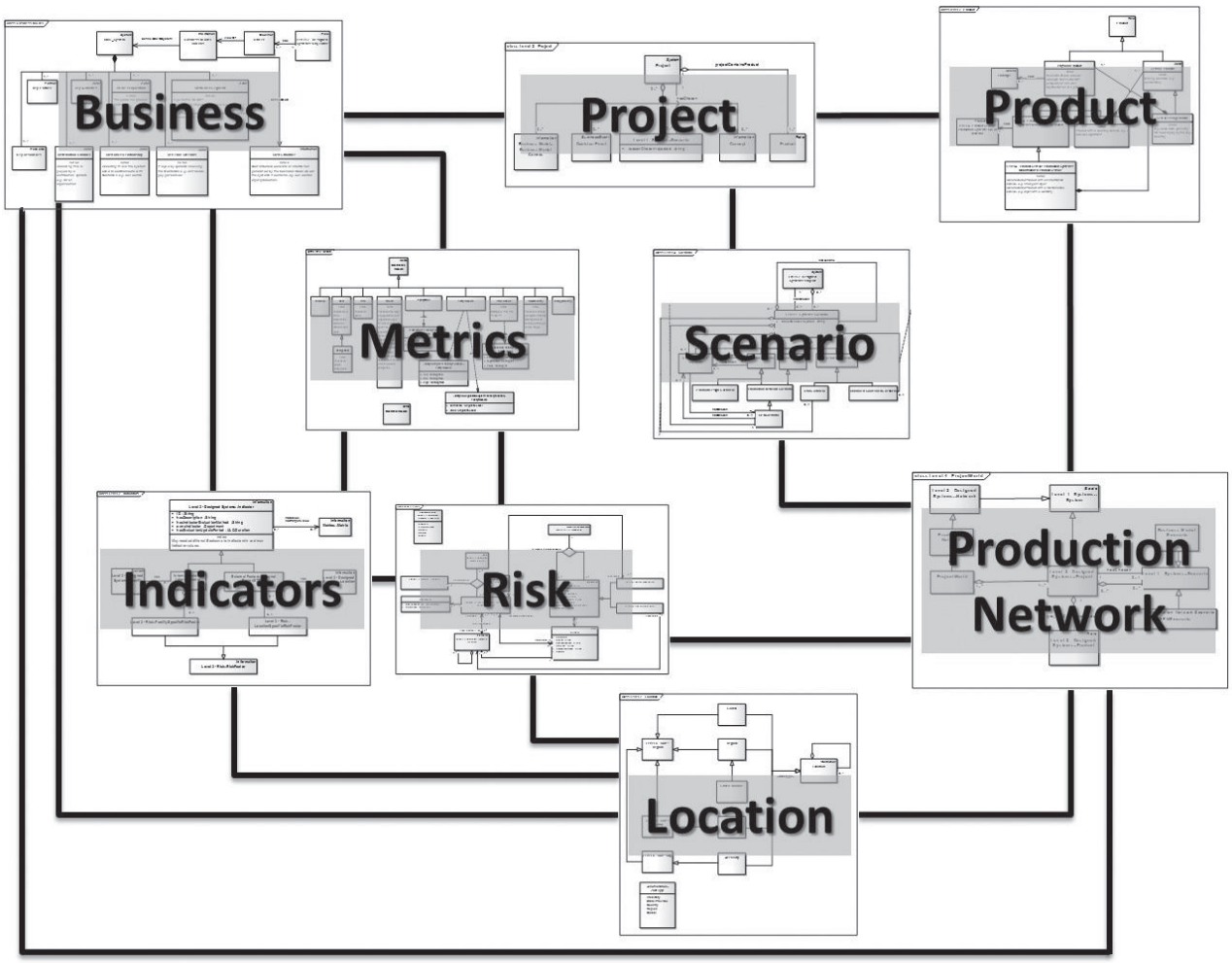


**Figure 1 — Range of reference information needed to support production network configuration decisions**


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# Industrial automation systems and integration — Formal semantic models for the configuration of global production networks

## 1 Scope

This document specifies a formal logic-based concept specialization approach to support the development of manufacturing reference models that underpin the necessary business specific knowledge models needed to support the configuration of global production networks.

This document specifies the following:

— the formal sematic model approach;

— hierarchical levels for property specialization;

— contexts for each level;

— key properties at each level;

— property relationships;

— property axioms;

— applicability rules.

The following are within the scope of this document:

— production networks for discrete product manufacture;

— formal semantics for the configuration of global production networks;

— system level formal semantics;

— designed system formal semantics;

— manufacturing business system formal semantics;

— global production systems network formal semantics.

The following are outside the scope of this document:

— in-factory formal semantics;

— formal semantics for the operation of global production networks.

## 2 Normative references

There are no normative references in this document.

## 3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

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— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

**3.1**
**activity**
**function**
function that transforms *inputs* (3.26) to *outputs* (3.38)

[SOURCE: ISO/IEC/IEEE 31320-1:2012, 2.1.53, modified — Adapted from definition of "function".]

**3.2**
**actor**
*role* (3.50) that is played by an *activity* (3.1)

Note 1 to entry: Actors are *processes* (3.41) that perform *functions* (3.1).

EXAMPLE A facility can act as a *supplier* (3.55), or as a *producer* (3.42), or as a *customer* (3.12).

**3.3**
**axiom**
well-formed formula in a formal *language* (3.28) that provides *constraints* (3.10) on the interpretation of symbols in the lexicon of a language

[SOURCE: ISO 18629-1:2004, 3.1.1]

**3.4**
**basic**
representation of an *entity* (3.19) or an *activity* (3.1)

Note 1 to entry: A basic requires no other concept to provide a *context* (3.11).

**3.5**
**bill of materials**
**BOM**
listing of all the subassemblies, parts and/or *materials* (3.30) that are used in the production of a *product* (3.43), including the quantity of each material required to make a product

Note 1 to entry: Adapted from IEC 62264-1:2013.

**3.6**
**business event**
*event* (3.20) that occurs in the business domain

**3.7**
**business process**
construct that represents a partially ordered set of business *processes* (3.41) or *enterprise* (3.18) *activities* (3.1), or both, that can be executed to realize one or more given objectives of an enterprise or a part of an enterprise to achieve some desired end-result

Note 1 to entry: Adapted from ISO 18629-1:2004.

**3.8**
**cardinality**
*constraint* (3.10) on the number of *entity* (3.19) *instances* (3.27) that are related to the subject entity through a *relationship* (3.47)

Note 1 to entry: Adapted from ISO/IEC 15474-1:2002, 4.2.


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**3.9**
**control**
condition or set of conditions required for a *function* (3.1) to produce correct *output* (3.38)

[SOURCE: ISO/IEC/IEEE 31320-1:2012, 2.1.32]

**3.10**
**constraint**
rule that specifies a valid condition of *data* (3.13)

[SOURCE: ISO/IEC/IEEE 31320-2:2012, 3.1.41 (B)]

**3.11**
**context**
immediate environment in which a *function* (3.1) operates

[SOURCE: ISO/IEC/IEEE 31320-1:2012, 2.1.30]

**3.12**
**customer**
organization or person that receives a *product* (3.43)

[SOURCE: ISO/IEC/IEEE 26511:2011, 4.6, modified — The words "or service" have been deleted at the end of the definition and the note to entry has been deleted.]

**3.13**
**data**
character strings, words or numbers without any given *context* (3.11)

**3.14**
**date**
string that specifies a date

Note 1 to entry: Aligned with the Highfleet Ontology Library Reference definition of "date" (see Annex A).

**3.15**
**decision event**
*event* (3.20) where decisions are made or taken

**3.16**
**end event**
end of a *process* (3.41) sequence

Note 1 to entry: A specialized type of *basic* (3.4) which has an *input* (3.26) *role* (3.50) only.

**3.17**
**energy**
quantity characterizing the ability of a *system* (3.56) to do work

[SOURCE: ISO 772:2011, 1.134]

**3.18**
**enterprise**
group of organizations sharing a set of goals and objectives to offer *products* (3.43), *services* (3.53) or both

[SOURCE: ISO 14258:1998, 2.1.1]

**3.19**
**entity**
concrete or abstract thing in the domain under consideration

[SOURCE: ISO 19439:2006, 3.29]

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**3.20**
**event**
construct that represents a solicited or unsolicited fact indicating a state change in the *enterprise* (3.18) or its environment

Note 1 to entry: Aligned with the Highfleet Ontology Library Reference definition of "event" (see Annex A).

[SOURCE: ISO 19440:2007, 3.1.33], modified — Original note to entry has been replaced by a new note to entry.

**3.21**
**facility function**
*function* (3.1) in an organization that performs one or more specific *activities* (3.1) by the provision of *resources* (3.49) in a given global *location* (3.29)

**3.22**
**flow**
*relationship* (3.47) from an *input* (3.26) to an *output* (3.38) or from an output to an input

Note 1 to entry: This is consistent with the Athena[28] definition: a flow is a relationship between two decision points: *process* (3.41) *roles* (3.50) [input, output, *control* (3.9), or *resource* (3.49)] or *gateways* (3.23) in a process.

**3.23**
**gateway**
element used to control how *process* (3.41) *flows* (3.22) interact as they converge and diverge within a *network* (3.35)Note 1 to entry: Adapted from Object Management Group[33] .

**3.24**
**global production network**
**GPN**
specialization of a *production network* (3.44), which contains *roles* (3.50) played by globally dispersed facilities

**3.25**
**information**
*data* (3.13) put in *context* (3.11)

EXAMPLE Facts, concepts, or instructions.

[SOURCE: ISO 10303-1:1994, 3.2.20, modified — The original definition is given as an example and a new definition has been provided.]

**3.26**
**input**
that which is transformed by an *activity* (3.1) into *output* (3.38)

[SOURCE: ISO/IEC/IEEE 31320-1:2012, 2.1.62, modified — The words "a function" have been replaced by "an activity".]

**3.27**
**instance**
individual occurrence of a *property* (3.46)

Note 1 to entry: This is distinct from the ":Inst" directive, which states what a property instantiates (see B.2.3).

Note 2 to entry: Adapted from ISO/IEC 15474-1:2002, 4.2.

**3.28**
**language**
combination of a lexicon and a grammar

[SOURCE: ISO 18629-1:2004, 3.1.12]


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**3.29**
**location**
site or position

**3.30**
**material**
representation of an *entity* (3.19) that is comprised of physical materials

**3.31**
**manufacturer**
business *enterprise* (3.18) that is involved in the full *product* (3.43) life cycle

Note 1 to entry: The product life cycle includes the product design, production, operation and end of life phases.

**3.32**
**manufacturing**
*function* (3.1) or act of converting or transforming *material* (3.30) from raw material or semi-finished state to a state of further completion

[SOURCE: ISO 15531-1:2004, 3.6.22, modified — Note to entry has been deleted.]

**3.33**
**manufacturing network**
*network* (3.35) which is concerned with full life cycle of a *manufactured product* (3.34)

Note 1 to entry: The life cycle of a manufactured product includes the design, production, operation and end of life phases.

**3.34**
**manufactured product**
*product* (3.43) that exploits/consumes a raw *material* (3.30)

**3.35**
**network**
arrangement of nodes and interconnecting branches

[SOURCE: ISO/IEC 2382:2015, 2121314, modified — Notes to entry have been deleted.]

**3.36**
**ontology**
logical structure of the terms used to describe a domain of knowledge, including both the definitions of the applicable terms and their *relationships* (3.47)

[SOURCE: IEEE 1175-1:2002, 3.9]

**3.37**
**organization function**
key *function* (3.1) that an *enterprise* (3.18) provides

**3.38**
**output**
that which is produced by an *activity* (3.1)

[SOURCE: ISO/IEC/IEEE 31320-1:2012, 2.1.89, modified — The words “a function” have been replaced by “an activity”.]

**3.39**
**physical product**
*entity* (3.19) that plays the *role* (3.50) of a *product* (3.43)

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**3.40**
**plan**
account of intended future course of action aimed at achieving specific goal(s) or objective(s) within a specific timeframe

**3.41**
**process**
structured set of *activities* (3.1), involving various *enterprise* (3.18) *entities* (3.19), that is designed and organized for a given purpose

[SOURCE: ISO 15531-1:2004, 3.6.29, modified — Note to entry has been deleted.]

**3.42**
**producer**
business *enterprise* (3.18) that produces goods or *services* (3.53) for sale

**3.43**
**product**
*role* (3.50) played by an *entity* (3.19) or *service* (3.53), or some combination of both, that is developed to be sold

**3.44**
**production network**
specialization of a *manufacturing network* (3.33) which is concerned with producing a *product* (3.43)

**3.45**
**project**
planned undertaking with specified targets

**3.46**
**property**
**class**
predicate that can apply to one *entity* (3.19) at a time and is used describe what the entity is

Note 1 to entry: Properties make up the taxonomic component of the *ontology* (3.36).

Note 2 to entry: The term "property" is used because the ontologies are semantic (modelling meaning) rather than set-theoretical (modelling categorizations).

**3.47**
**relationship**
real-world association among one or more *entities* (3.19)

Note 1 to entry: Adapted from ISO/IEC 15474-1:2002, 4.2.

**3.48**
**requirement**
condition or capability to be met or possessed by a *system* (3.56), *product* (3.43), *service* (3.53), result, or component to satisfy a contract, standard, specification, or other formally imposed document

Note 1 to entry: Adapted from Project Management Institute[34] .

**3.49**
**resource**
means used by an *activity* (3.1) to transform *input* (3.26) into *output* (3.38)

[SOURCE: ISO/IEC/IEEE 31320-1:2012, 2.1.71, modified — Adapted from definition of "mechanism", and the words "a function" have been replaced by "an activity".]


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**3.50**
**role**
part played by a *basic* (3.4) in an *activity* (3.1)

Note 1 to entry: A role cannot exist without a *context* (3.11).

Note 2 to entry: A *system* (3.56) provides a context for the roles it contains.

Note 3 to entry: To aid efficiency all roles are declared as pairwise disjoint.

Note 4 to entry: A basic can play more than one role.

**3.51**
**semantics**
meaning of the syntactic components of a *language* (3.28)

[SOURCE: ISO/IEC/IEEE 31320-2:2012, 3.1.175]

**3.52**
**scenario**
representation of a specific potential or actual configuration to achieve the functionality of a *system* (3.56)

Note 1 to entry: Different scenarios allow for different what-if analyses to be performed.

**3.53**
**service**
*system* (3.56) *function* (3.1) that plays the *role* (3.50) of a *product* (3.43)

**3.54**
**start event**
start of a *process* (3.41) sequence

Note 1 to entry: A specialized type of *basic* (3.4) which has an *output* (3.38) *role* (3.50) only.

**3.55**
**supplier**
facility in an organization that enters into an agreement with the acquirer for the supply of a *product* (3.43)

[SOURCE: ISO/IEC/IEEE 15288:2015, 4.1.45, modified — The words "organization or an individual" have been replaced by "facility in an organization", the words "or service" have been deleted at the end of the definition and the notes to entry have been deleted.]

**3.56**
**system**
combination of interacting *resources* (3.49) organized to achieve one or more stated purposes

[SOURCE: ISO/IEC/IEEE 15288:2015, 4.1.46, modified — The word "elements" has been replaced by "resources" and the notes to entry have been deleted.]

**3.57**
**system function**
*activity* (3.1) in a *system* (3.56) that transforms an *input* (3.26) set of elements into a set of *output* (3.38) elements

**3.58**
**timespan**
period of time with a start date and an end date where *date* (3.14) can be specified down to fractions of second

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# 4 Abbreviated terms

| | |
|---|---|
| BOM | Bill of Materials |
| KFL | Knowledge Frame Language (Highfleet) |
| CLIF | Common Logic Interchange Format (ISO/IEC 24707) |
| ECLIF | Extended Common Logic Interchange Format (Highfleet) |
| GPN | Global Production Network |
| IC | Integrity Constraint |
| MLO | Middle Level Ontology (Highfleet) |
| ULO | Upper Level Ontology (Highfleet) |
| UML | Unified Modelling Language (ISO/IEC 19501). |

# 5 Formal semantic models for the configuration of global production networks

## 5.1 Formal semantics

Reference models based on this document provide a formal semantic base with which application vendors shall conform if they are to maintain interoperability.

The concept specialization approach of this document, based on formal logic, provides a new dimension to the computational interpretation of models based on the document when compared to most existing production related standards. It ensures that users shall conform to the defined standardized constraints, through the use of its logic.

The Formal Semantic Models for the Configuration of Global Production Networks are expressed using the Knowledge Frame Language (KFL) and Extended Common Logic Interchange Format (ECLIF) from Highfleet Ontology Library Reference (see Annex A), both of which are based on Common Logic (ISO/IEC 24707). The KFL, ECLIF and the upper level concept definitions used in this document are provided in the annexes of this document.

NOTE Annex B provides a reference guide to the syntax and commonly used techniques for writing Knowledge Framework Language (KFL) files. Annex C contains information on ECLIF. Annex D outlines the FLEXINET approach.

## 5.2 Overview of the levels of specialization

The premise behind the formal semantic models for the configuration of global production networks is that for ease of construction, effective interoperability and flexible re-use enterprise ontologies shall be built from a common base that utilizes a common reference ontology wherever possible. A simple statement describes the basis of generalization: “A design of an ontology representing the core elements of a particular enterprise, will end up with a good number of elements that are not exclusive to this particular enterprise, but common to some other enterprises that operate in the same sector”.

Following this reasoning, it is inferred that a subset of the elements that are common to a particular sector shall be applicable or extrapolated to different sectors. In other words, some of the elements that are applicable to the Pumps Industry sector will also be applicable to the White Goods sector.

Both sectors are part of the manufacturing industry, so it is stated that the concepts that are widely applicable to different manufacturing sectors belong to the broader area of manufacturing industry, and not to a particular sector. In this area reside the elements that are specific to the manufacturing


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industry, but not necessarily for other industry sectors such as Finance, Assurance, Construction, Mining and Agriculture.

However, some of the concepts identified for manufacturing industry are applicable, in a generalized sense, to other industry sectors. In this case, they belong to the broader area of Designed Systems. This leads to a comprehensive set of general concepts and relations that shall be universally accepted and understood across the full range of business sectors.

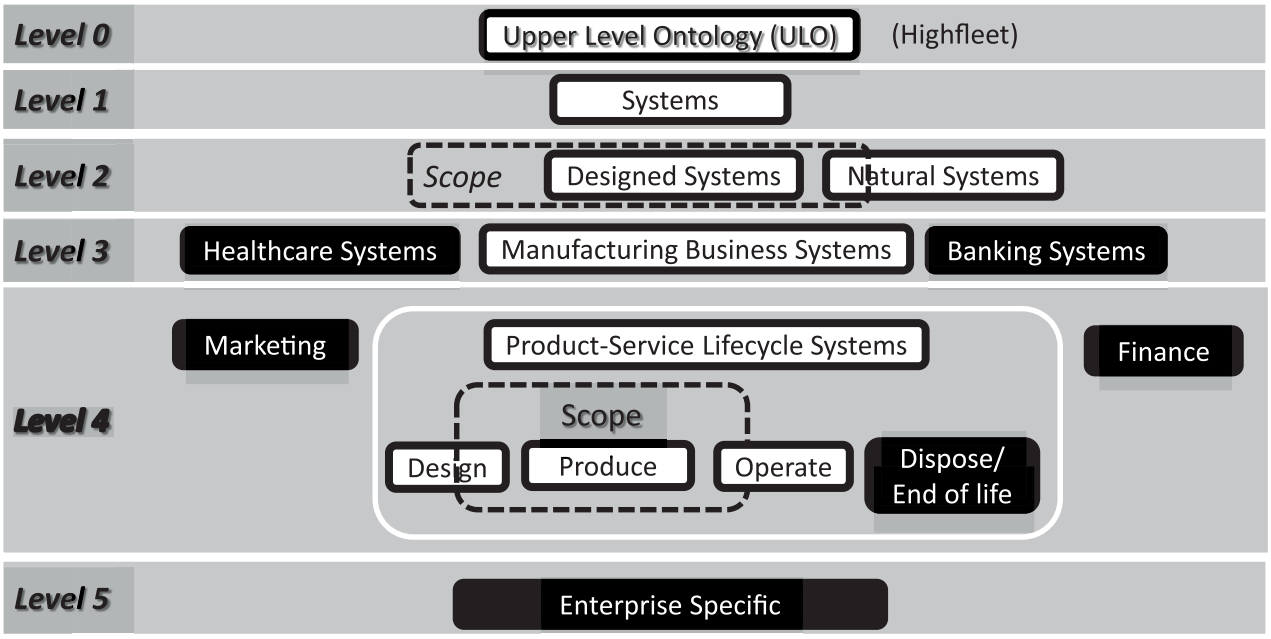


**Figure 2 — Levels of the formal semantic models for the configuration of global production networks approach**

To enable the management of complexity within the ontology and to facilitate re-use across enterprise specific domains the formal semantic models for the configuration of global production networks approach is organized into five levels, as illustrated in Figure 2. These levels are needed to specialize the concepts from the foundation level (level 0) to the enterprise specific level (level 5). Each level inherits concepts from the level above and provides a constraining influence on the subsequent level, the ontology becoming more domain specific (specialized) with each level. The contexts that are of relevance to this document are shown in Figure 2 in boxes with a pale background. The boxes with a dark background are illustrations of contexts that are outside the scope of this document.

The Level 0 Upper Level Ontology, which is fully generic, consists of foundation concepts applicable to all domains. The foundation concepts include time, events, aggregation and lists which, are derived from the Highfleet Upper Level Ontology (ULO) (see Annex A). The Highfleet ULO is based on OntoClean (Guarino and Welty, 2002[26]) and the subsequent Common Logic Standard (ISO/IEC 24707).

Level 1 starts from the premise that a systems context is fundamental to the definition of any systems based network. Level 1 therefore contains the few key generic concepts necessary to support the system functionality provision in any system.

Level 2 uses Banathy's classification to specialize systems into "Natural Systems" and "Designed Systems". Natural systems are living systems of all kinds, including the solar system and the Universe. Designed systems, are man-made creations, including fabricated physical systems, conceptual knowledge and purposeful creations.

Level 3 differentiates designed systems by specifying the business system context for subsequent applicable areas. A few are illustrated in Figure 2, but include manufacturing, healthcare, construction, tourism, grocery, farming, finance. Manufacturing Business Systems concepts are then further specialized within Level 4. Level 3 areas such as Healthcare Systems and Banking Systems would also

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possess areas providing relevant specializations at Level 4 and some of these areas can be similar to those within the Manufacturing Business Systems domain, however, the concepts contained would be specialized within the context of the parent area.

Level 4 contains concepts specifically relating to the Manufacturing Business Systems domain. The area considered at level 4 is Product-Service Lifecycle Systems, implemented in Global Production Networks. The lifecycle phases are denoted as design, produce, operate and end of life (including disposal, recycling and remanufacturing). The focus is how to design a GPN to produce and operate a product-service. The main area considered within the Product-Service Lifecycle is therefore "Produce" (producing the product-service) but the scope also overlaps into "Design" (of the network) and "Operate" as the operation of the product and the service needs to be considered in design.

Level 5 provides enterprise specific concepts for the product-service production domain for a specific enterprise. These shall be developed for each specific enterprise and be mapped to the reference ontology concepts in order to take advantage of the underlying structure that it provides.

# 6 System functionality formal semantics — Level 1

## 6.1 Overview

As stated in 5.2, Level 1 starts from the premise that a systems context is fundamental to the definition of any system based network. Level 1 therefore shall contain the few key concepts necessary to model any generic system's functionality. In a typical systems engineering approach a system is considered to transform inputs into outputs and is defined as "a combination of interacting elements organized to achieve one or more stated purposes" (ISO/IEC/IEEE 15288:2015; Athena 2006. This document focuses on the constructs to model system functions where the "interacting elements" in a system are represented as "basics" that play the role of "resource" while the "achieve one of more stated purposes" is represented by the "output" concept which in turn is linked to the "activity" and "system function" concept.

Figure 3 provides a visual illustration of the level 1 concepts and relations using Unified Modelling Language (UML) class diagrams. The full formal ontology formal ontology is then provided in the subclauses below, in terms of properties, relations and axioms. This same form of explanation is provided subsequently for each level.

One key aspect to the level 1 is the representation of Activity and System Function through the use of formalized IDEF0 concepts (PUBs 1993). The Activity concept being equivalent to an IDEF0 activity and the Roles of Input, Output, Resource and Control playing the part of IDEF0 flows. An Input represents what is brought into and is transformed or consumed by the activity to produce Outputs. A Control is a specialized Input that provides a condition required to produce the correct activity output (PUBs 1993; Athena 2006). Resource represents the means by which an activity is performed.

Another key aspect is the definition of the two main parent classes at level 1; those of Basic and Role. A Basic concept is independent of the system or context so its definition does not depend on any other concept and an instance of a Basic always retains its identity. Role defines how Basics are used in any particular System.

Basics occurring at level 1 are classified as Activity and Entity, with an Entity being anything of interest. Subtypes of Entity at level 1 are Information, Material and Energy. Note that Material is used to denote any material thing and not raw materials. A Basic can be comprised of Basics.

EXAMPLE 1 "Bottled water" comprised of the Materials "bottle", "cap" and "mineral water".

This recursion can also be applied to Activity to represent sub-activities or System Functions to represent systems of systems functionality. An Activity is also a subtype of Basic and provides a context for the Roles that other Basics play in its performance.


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Role depends on the Activity for its context and an instance of a Role cannot exist without such a context. Basics are used to play a Role within an Activity.

EXAMPLE 2 A person Joe may have a Role as a lecturer in a university i.e. he plays the Role of a Resource in the context of a university activity. If the university closes the lecturer role ceases to exist whereas the person Joe (an instance of a Basic) will still be present.

EXAMPLE 3 Consider two manufacturing companies X and Y, with X selling a machine to dry clothes and Y selling a clothes-drying service. In Company X a drying machine plays the Role of an output (a product). In company Y the drying machine plays the Role of a Resource to support the service activity whose output is the service. Hence the Role of the drying machine changes whereas the Basic "drying machine" is always a "drying machine".

Roles can be comprised of Roles,

EXAMPLE 4 A lecturer Role can be allowed to be comprised of administration, teaching and research Roles.

Additionally, there is no specific requirement for a Role to be played by a Basic, enabling empty Roles to be modelled.

EXAMPLE 5 If a person Joe left his Role as a lecturer the Role of lecturer would still exist but as a lecturer vacancy.

A Basic playing a Role for certain period of time is represented using the TimeSpan concept and modelled using the relation "playsRole".

EXAMPLE 6 In the context of a manufacturing organization system, the Basic "drying machine" can play the Role of a Product during the TimeSpan of that business system. If the company moves across fully to providing a drying service then the TimeSpan of the dryer as a product will come to an end.

Roles are also represented as being played within a Scenario, so the playsRole relation is a quaternary relation. The Scenario concept has been provided in order to represent alternative ways of meeting the same overall system functional requirements i.e. in production terms each scenario provides one way of providing the system output. Alternative scenarios offer the potential for companies to perform 'what-if" analysis on each alternative.

EXAMPLE 7 A manufacturer can use a supplier from Germany in one scenario and in another to use a supplier from Japan.

The concept of Role here is well aligned with that of ISO 19440, although at this level no distinction is drawn between people, machine or product roles, as these would be specializations at a lower level. The ideas of Roles also share views with those of Kozaki *et al*. (2006), Kozaki *et al*. (2008) and Mizoguchi *et al*. (2012). In common with those views, the concepts of Basic, Role and Role aggregation are captured. However in this approach Time and Role context are explicitly modelled.

A Basic can affect the state of a role.

EXAMPLE 8 The size of a Basic "bottled water" playing the Role of a product can influence the dimensions required for a packing resource Role.

Additionally a Role can affect the state of a Role.

EXAMPLE 9 Within the lecturer Role more duties allotted to the administration Role would cause duties to be removed from the teaching Role.

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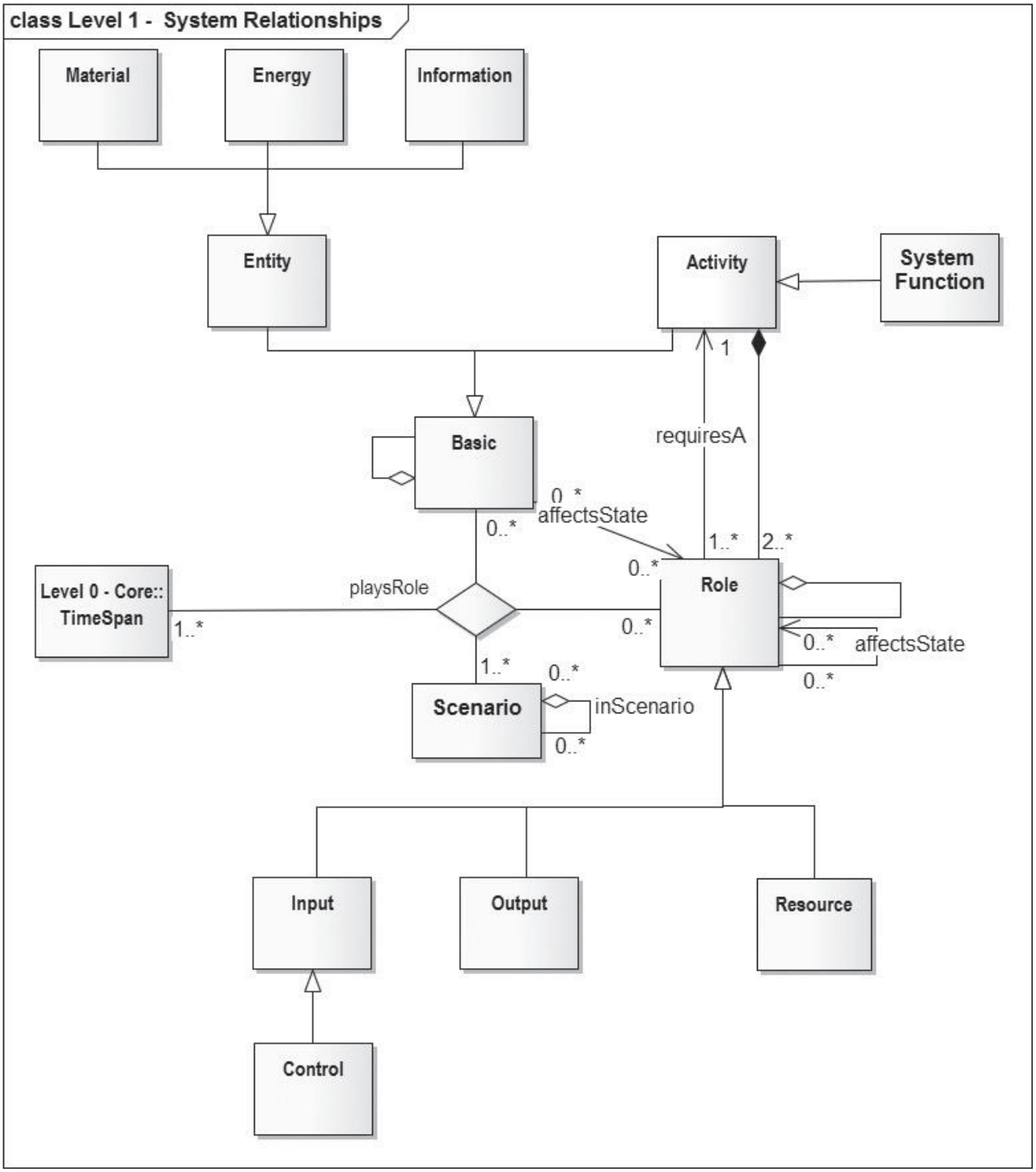


**Figure 3 — Level 1 UML class diagram**

## 6.2 Level 1 formal semantics — Context

### 6.2.1 Context

KFL notation for context:

:Use MLO

:Ctx 1SYSCtx


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:Inst UserContext

:supCtx MLO

## 6.3 Level 1 formal semantics — Properties

### 6.3.1 Property — Basic

KFL notation for basic:

:Prop Basic

:Inst Type

:Inst NonLogicalFunctor

:sup Particular

:rem "represents an entity or an activity. A Basic concept is independent of the <sym>1SYSCtx.Activity</sym> or context, its definition does not depend on another concept. At the Systems level a Basic can be classified as <sym>1SYSCtx.Activity</sym> or <sym>1SYSCtx.Entity</sym>."

### 6.3.2 Property — Entity

KFL notation for entity:

:Prop Entity

:Inst Type

:Inst NonLogicalFunctor

:sup Basic

:partitionedBy (listof Energy Material Information)

:rem " any concrete or abstract thing in the domain under consideration. A <sym>1SYSCtx.Basic</sym> which is not a <sym>1SYSCtx.Activity</sym>."

### 6.3.3 Property — Activity

KFL notation for activity:

:Prop Activity

:Inst Type

:sup Basic

:sup MLO.Object

:rem " A function that transforms *inputs* to *outputs*."

(disjointSubProps Activity)

### 6.3.4 Property — System function

KFL notation for system:

:Prop SystemFunction

:Inst Type

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:sup Activity

:sup MLO.Object

:rem “the activity in a system that transforms an input set of elements into a set of output elements that may be the same or measurably different from the input set"

(disjointSubProps SystemFunction)

### 6.3.5 Property — Energy

KFL notation for energy:

:Prop Energy

:Inst Type

:Inst NonLogicalFunctor

:sup Entity

:rem "The capacity of a body or <sym>1SYSCtx.System</sym> to do work. Can be an integer so modelled as a <sym>MLO.NonLogicalFunctor</sym>.

Properties subsumed by Energy should also be subsumed by <sym>MLO.ConcreteEntity</sym> or <sym>MLO.AbstractEntity</sym>"

(disjointSubProps Energy)

### 6.3.6 Property — Material

KFL notation for material:

:Prop Material

:Inst Type

:sup Entity

:sup MLO.Object

:rem "an entity that is comprised of physical materials. An <sym>MLO.Object</sym> is anything that has a location in time and space."

(disjointSubProps Material)

### 6.3.7 Property — Information

KFL notation for information:

:Prop Information

:Inst Type

:Inst NonLogicalFunctor

:sup Entity

:rem "Information is data put in context; it is related to other pieces of data. Can be a number so modelled as a <sym>MLO.NonLogicalFunctor</sym>. Properties subsumed by Information should also be subsumed by <sym>MLO.ConcreteEntity</sym> or <sym>MLO.AbstractEntity</sym>."

(disjointSubProps Information)


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### 6.3.8 Property — Role

KFL notation for role:

:Prop Role

:Inst Type

:sup MLO.AbstractEntity

:disjointWith Basic

:rem "The part played by a basic in an activity. Role type includes all of the types of <sym>MLO. AbstractEntity</sym> terms that participate in activities. A Role cannot exist without a context. A <sym>1SYSCtx.SystemFunction</sym> provides a context for the Roles it contains. To aid efficiency all Roles are declared as pairwise disjoint. A Basic can play more than one role."

### 6.3.9 Property — Input

KFL notation for input:

:Prop Input

:Inst Type

:sup Role

:rem "that which is transformed by an activity into output."

### 6.3.10 Property — Output

KFL notation for output:

:Prop Output

:Inst Type

:sup Role

:rem "that which is produced by an activity."

### 6.3.11 Property — Resource

KFL notation for resource:

:Prop Resource

:Inst Type

:sup Role

:rem " the means used by an activity to transform *input* into *output* "

### 6.3.12 Property — Control

KFL notation for control:

:Prop Control

:Inst Type

:sup Input

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:rem "condition or set of conditions required for a function to produce correct output. A control is also an input."

### 6.3.13 Property — Scenario

KFL notation for scenario:

:Prop Scenario

:Inst Type

:sup AbstractEntity

:rem " represents a specific potential or actual configuration to achieve a system's functionality."

:disjointWith Role

:disjointWith Basic

(disjointSubProps Scenario)

## 6.4 Level 1 formal semantics — Relationships

### 6.4.1 Relationship — Affects state

KFL notation for affects state:

:Rel affectsState

:Inst BinaryRel

:Inst RigidRel

:Inst AsymmetricBR

:Sig Particular Role

:Args "Affector" "Role"

:lex "?1 affects Role ?2"

:rem "affectsState is unidirectional so is an AsymmetricBR"

### 6.4.2 Relationship — Basic affects role

KFL notation for basic affects the state of a role:

:Rel basicAffectsState

:Inst BinaryRel

:Inst RigidRel

:supRel affectsState

:Sig Basic Role

:Args "Basic" "Role"

:lex "Basic entity ?1 affects Role ?2"

:rem "basicAffectsState holds between Basic individuals and Role individuals."


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### 6.4.3 Relationship — Role affects the state of role

KFL notation for role affects the state of a role:

:Rel roleAffectsState

:Inst BinaryRel

:Inst RigidRel

:supRel affectsState

:Sig Role Role

:Args "Role" "Role"

:lex "Role ?1 affects Role ?2"

:rem "roleAffectsState holds between Role individuals and Role individuals."

### 6.4.4 Relationship — Plays role

KFL notation for plays role:

:Rel playsRole

:Inst TernaryRel

:Inst NonRigidRel

:Sig Basic Role Scenario

:Args "Basic" "Role" "Scenario"

:lex "Basic entity ?1 plays Role ?2 in Scenario ?3"

:rem "A basic plays a role in a scenario. To provide a <sym>RootCtx.TimeSpan</sym> use the ECLIF operator <sym>holdsIn</sym>."

### 6.4.5 Relationship — Role requires a context provided by an activity

KFL notation for a role requires a context provided by an activity:

:Rel requiresA

:Inst BinaryRel

:Inst RigidRel

:Sig Role Activity

:Args "Role" "Activity"

:lex "Role ?1 depends on Activity ?2"

:rem "A role requires a context provided by one activity."

(functionalArg requiresA 2)

### 6.4.6 Relationship — Basic composed of a basic

KFL notation for basic contains a basic:

:Rel basicContainsBasic

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:Inst BinaryRel

:Inst RigidRel

:Inst AntisymmetricBR

:Sig Basic Basic

:Args "sup" "sub"

:lex "?1 is composedOf ?2"

:rem "sup contains sub. Given that sup and sub are not identical, then it is not the case that sub contains sup."

### 6.4.7 Relationship — Role composed of a role

KFL notation for Role contains a role:

:Rel roleContainsRole

:Inst BinaryRel

:Inst RigidRel

:Inst AntisymmetricBR

:Sig Role Role

:Args "sup" "sub"

:lex "?1 is composedOf ?2"

:rem "sup contains sub. Given that sup and sub are not identical, then it is not the case that sub contains sup."

### 6.4.8 Relationship — Activity contains a role

KFL notation for activity contains a role:

:Rel activityContainsRole

:Inst BinaryRel

:Inst RigidRel

:Sig Activity Role

:Args "Activity" "Role"

:lex "Activity ?1 contains Role ?1"

## 6.5 Level 1 formal semantics — Axioms

### 6.5.1 Axiom — Role requires an activity to provide a context

ECLIF notation for ‘a role requires an activity to provide a context’:

:Name "1SYS - Axioms"

:Description "Axioms pertaining to relations occurring at the Systems level."

:Use 1SYSCtx


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```
(=> (Role ?r)
 (exists (?a)
      (and (Activity ?a)
           (requiresA ?r ?a))))
:IC hard "The Role ?r requiresA Activity to provide a context."
```

### 6.5.2 Axiom — An activity cannot contain a role and play the role

ECLIF notation for ‘an activity cannot contain a role and play the role’:

```
(=> (and (Activity ?activity)
   (playsRole ?activity ?role ?scenario)
   )
    (not(activityContainsRole ?activity ?role)))
:IC hard "The same Activity cannot contain a Role and play the Role. ?activity playsRole ?role in Scenario ?scenario. The relation activityContainsRole does not hold between ?activity and ?role."
```

## 6.6 Level 1 formal semantics — Rules

### 6.6.1 Rule — Role requires an activity

ECLIF notation for ‘role requiring an actvity:

```
:Name "1SYS - Rules"
:Use 1SYSCtx
(=> (requiresA ?x ?y)
   (activityContainsRole ?y ?x))
;;;A Role requiring an activity as a context implies that the Activity contains the Role
```

### 6.6.2 Rule — Activity containing a role

ECLIF notation for ‘activity containing a role’:

```
(=> (activityContainsRole ?x ?y)
   (requiresA ?y ?x))
;;;An Activity containing a Role implies that the Role requires the Activity as a context
```

# 7 Designed systems formal semantics — Level 2

## 7.1 Overview

As mentioned in the introduction and illustrated in Figure 1, there are many semantic models that impinge on decision-making concerning the configuration and re-configuration of global production networks. This document focuses on production network concepts, but includes some general definitions for related concepts that should ideally be developed in or drawn from other future standards. The concept for location is a good example of such a concept. This is needed to identify the global location of

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production facilities, but this is a narrow definition compared with the potential full range of location information requirements.

### 7.1.1 Level 2 Systems overview

There are many potential activities that can be described at level 2 as system functions that are relevant to designed systems. Figure 4 provides a UML class diagram that depicts a selection of these that have relevance to manufacturing system functions.

NOTE Of those that are shown, the System Functions that are directly relevant to this document are Organization Function, Facility Function and Project. The facilities in an organization provide the key system elements in configuring a production network to achieve some overall functionality. The Project concept represents the functions to be performed against some new task, in this case related to a production network configuration task. It also provides a concept that can be expanded to include product design and business modelling activities in future standards development.

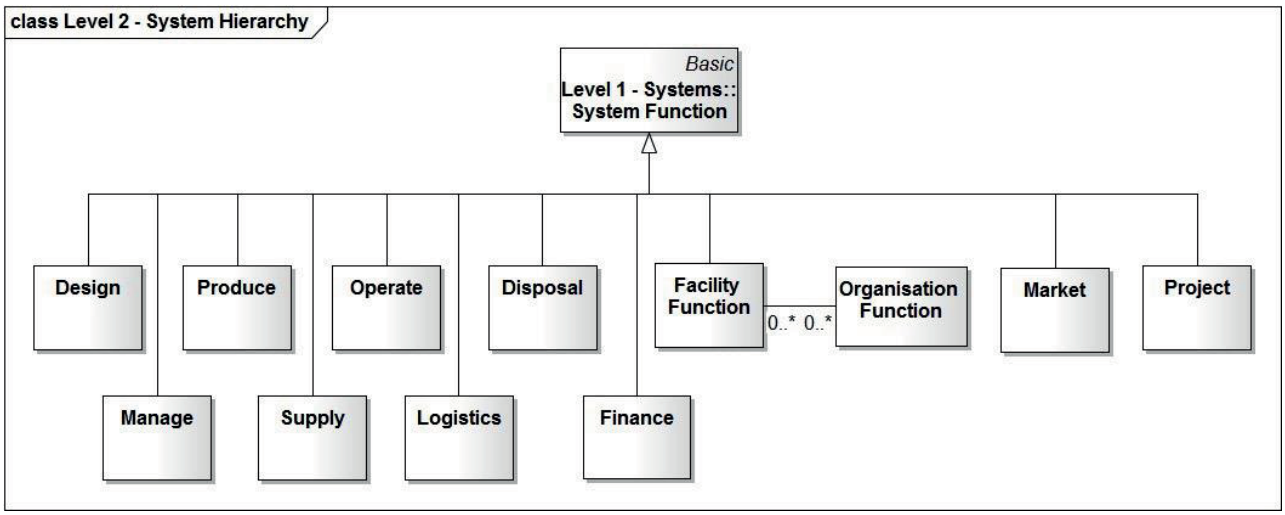


**Figure 4 — UML class diagram depicting system functions at level 2**

### 7.1.2 Level 2 Role overview

As explained in 6.1, the concept Role provides a view on how Basics are used in any particular System. The same "basic" business can be considered to be playing the role of

a) a manufacturer when considering how things are made;

b) a supplier when considering what it is going to offer to potential customers, or

c) a customer when considering what it needs to purchase from other suppliers.

The term Actor has been introduced to indicate roles that can be played by System Functions. A few examples of possible Actors are illustrated in Figure 5 with those that are of particular importance to this document being Supplier, Manufacturer, Producer, Customer and Service Provider.

Similarly Entities can also play roles in particular systems.

EXAMPLE 1 A machine tool (a Material Entity) can play the role of a Resource in a machine shop operation.

EXAMPLE 2 An order (an Information Entity) can play the role of an Input in a scheduling operation.


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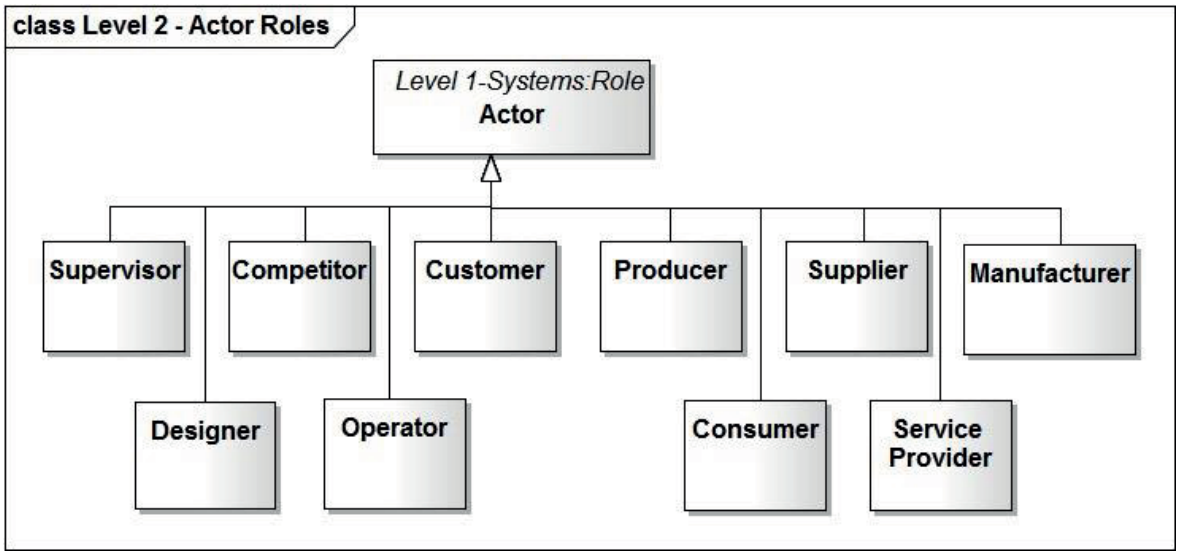


**Figure 5 — UML class diagram depicting roles, especially actor roles**

### 7.1.3 Level 2 Network overview

The UML diagram depicted in Figure 6 illustrates the concepts and relations for the level 2 representation of a network. This defines a network as a scenario that captures an arrangement of nodes as System Functions and Gateways while Flows between Inputs and Outputs provide the interconnecting branches. This model is in line with process modelling techniques in general use but also adds the potential for the logical constraints to be included. The concepts and relations are modelled in 7.2 and 7.3, while the logical constraints that are added in this document through the formal axioms are defined in 7.5.

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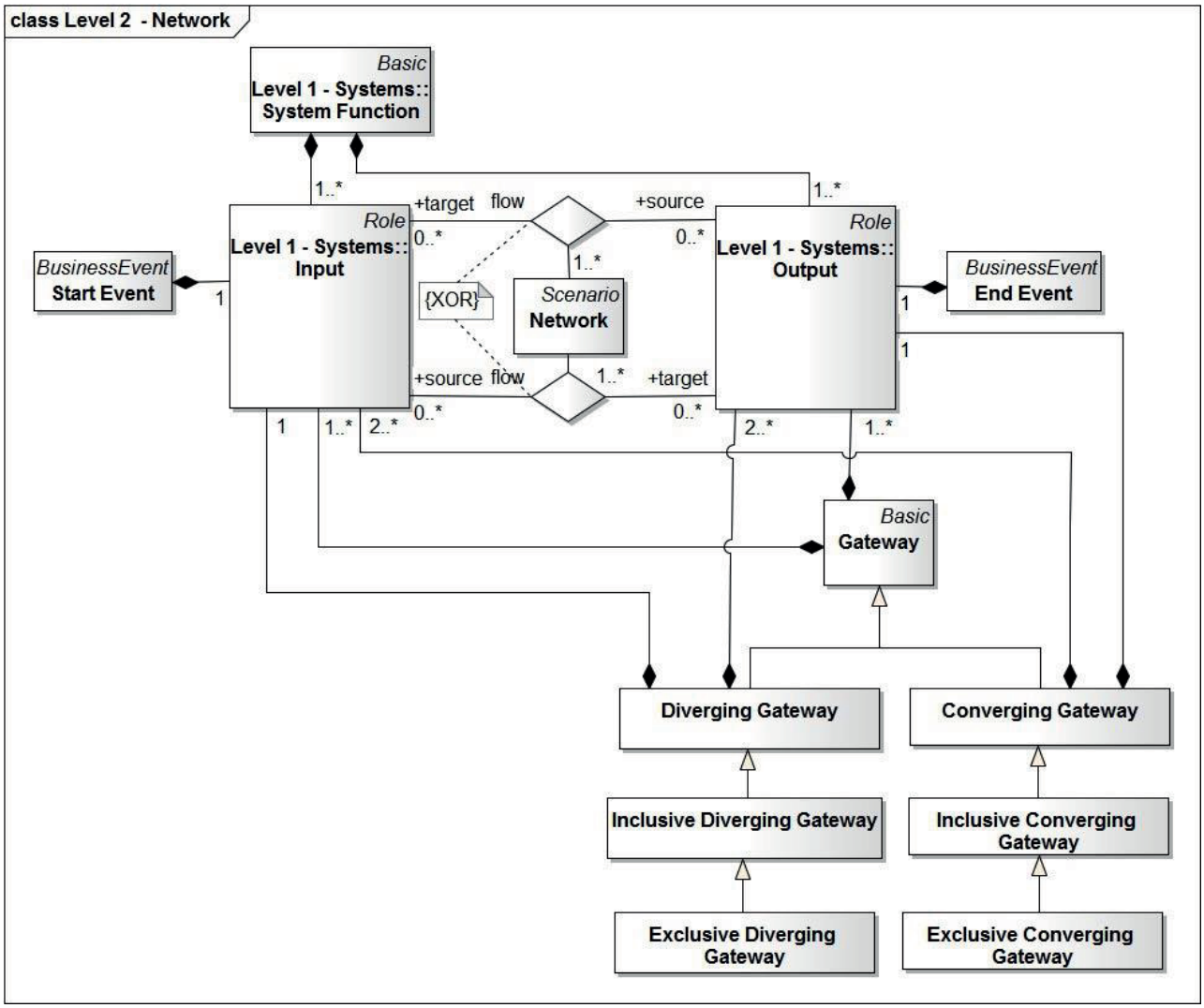


**Figure 6 — UML class diagram depicting the representation of network at level 2**

### 7.1.4 Product overview at levels 2 and 4

Figure 7 provides the UML class diagram of Product relevant to this document that seeks to model the key concepts and relationships that are significant to distinguish between physical products and services that are offered for sale. It is not intended to model the concept of product beyond this requirement, along with the necessary link from a physical manufactured product to its bill of materials, in order to provide a link to potential suppliers.

In this document a product is defined as an Entity or Service or some combination of both that is developed to be sold i.e. the Product is an Entity or Service that is playing the role of a Product. The term PhysicalProduct is used to denote an Entity playing the role of a Product. The term Service is used to denote a System Function that plays the role of a Service.

EXAMPLE 1 A machine tool being sold by a machine tool manufacturer is a Material Entity playing the role of a Product.

EXAMPLE 2 A will being sold by a solicitor is an Information Entity being sold as a Product.

EXAMPLE 3 A volume of gas being supplied to a consumer is an Energy Entity playing the role of a Product.


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Service is defined as system function that is sold as a Product i.e. rather than a physical thing, a Service is a function that has some value that can therefore be sold as product.

EXAMPLE 4 Advice from a consultant can be sold as a Product.

Many Service products will also exploit a physical product and these are denoted as ServiceUsingPhysicalProduct.. In these cases the purchase is for the use of the physical product and not for the physical product itself.

EXAMPLE 5 Power by the Hour is a Service which requires an aero engine.

EXAMPLE 6 A lease car requires the use of a car.

Physical Products can also include a Service element which is part of the product and these are denoted by the term PysicalProductWithService.

EXAMPLE 7 A washing machine with a maintenance contract.

A "Manufactured Product" is a product that consumes raw materials in order to produce physical entities. A Bill of Material is a list of all parts required to manufacture and assemble the Manufactured Product.

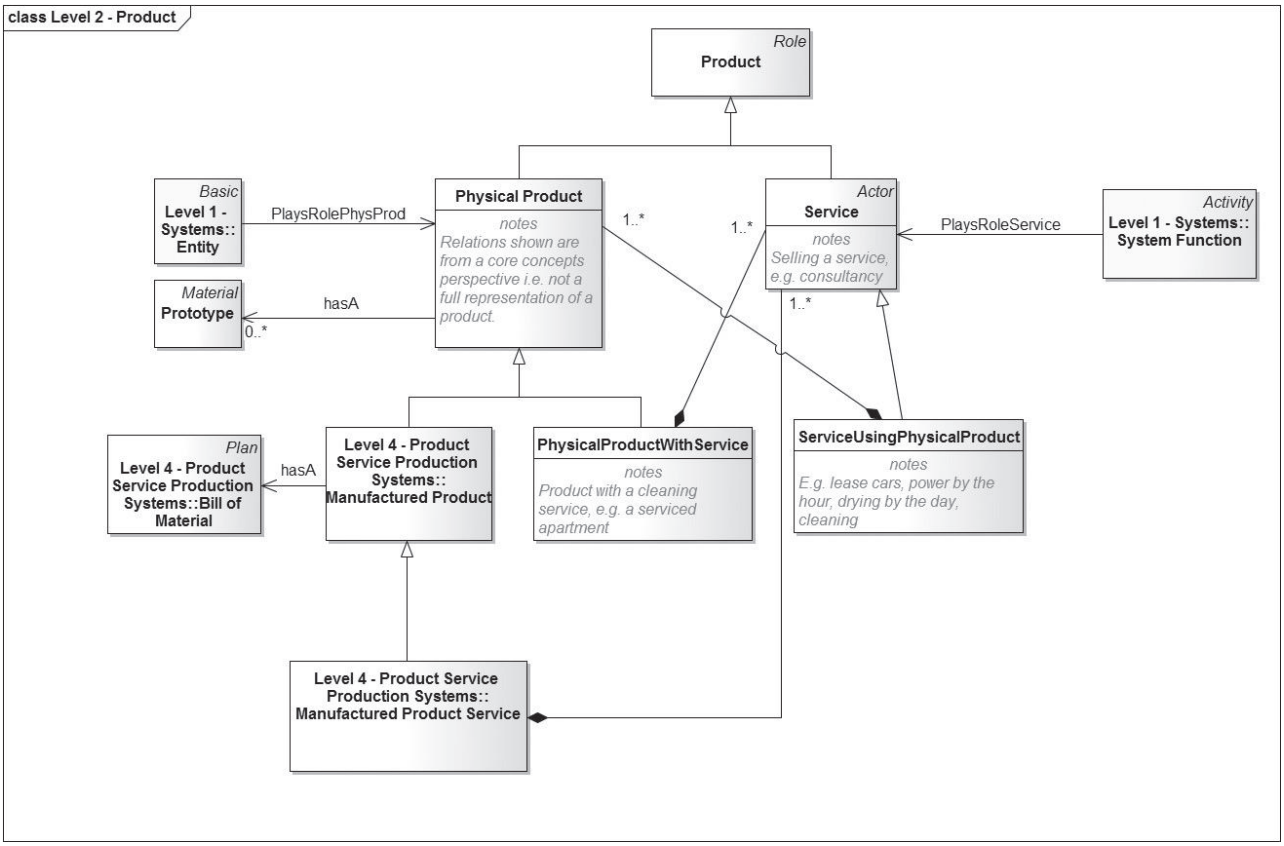


**Figure 7 — UML class diagram depicting the representation of product at levels 2 and 4**

### 7.1.5 Overview of Location

Location is an important concept for globally based decision making. The appropriate definitions for Location are dependent on use and can be difficult to define precisely as location boundaries are often determined by human demarcation (Smith & Varzi, 2000). In this document, to support decisions related to global production networks, the concepts and relations shown in Figure 8 have been used. As mentioned at the start of Clause 7, a future standard that defines an ontology for location that can be commonly exploited across industrial data standards would be of great benefit.

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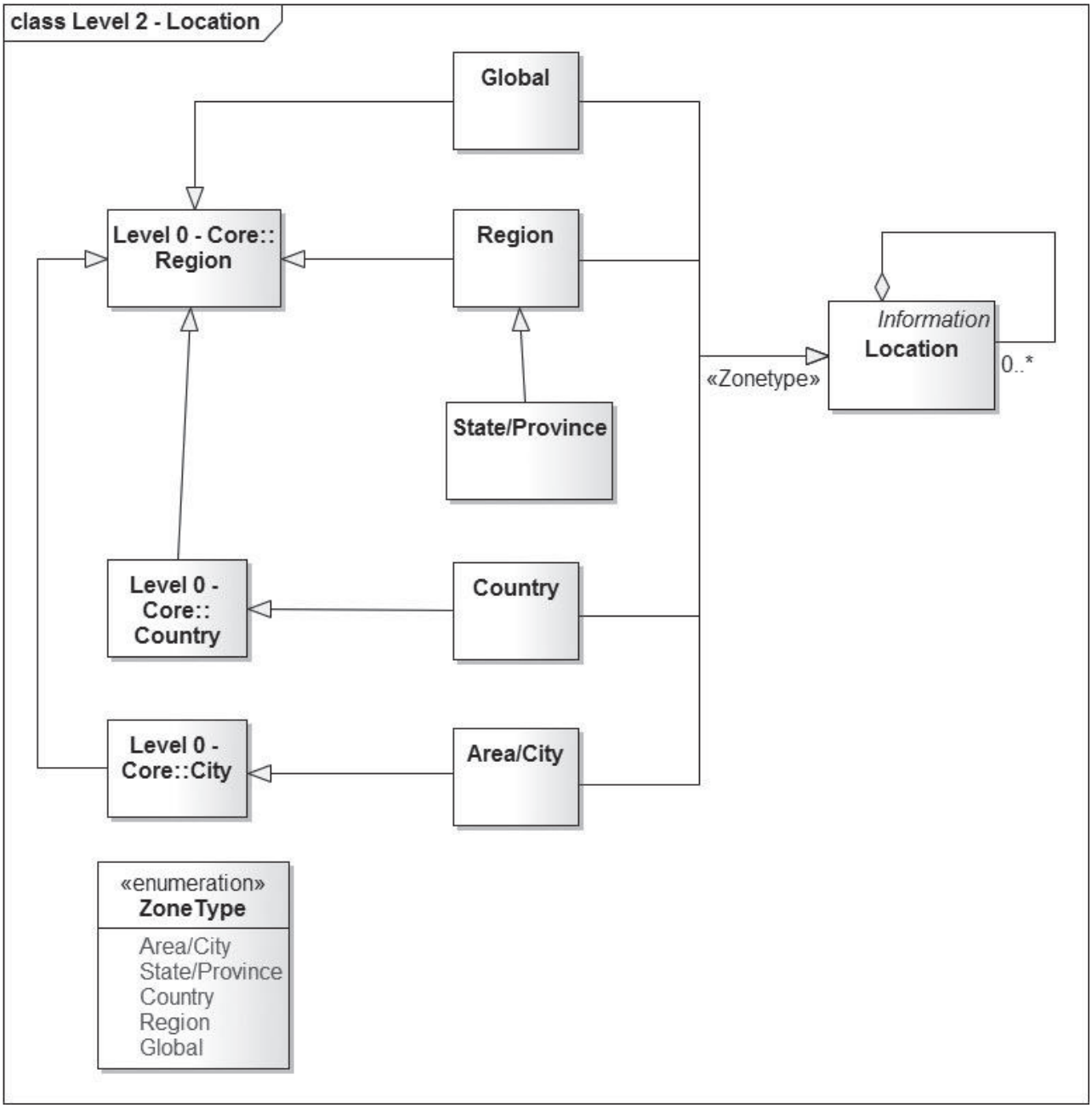


**Figure 8 — UML class diagram depicting the representation of location**

## 7.2 Level 2 formal semantics — Context

### 7.2.1 Context — Designed systems

KFL notation for the level 2 designed systems context:

:Ctx 2DSCtx

:Inst UserContext

:supCtx ../1SYSCtx


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## 7.3 Level 2 formal semantics — Properties

### 7.3.1 Property — Network

KFL notation for network:

:Prop Network

:Inst Type

:sup Scenario

:rem "arrangement of nodes and interconnecting branches. The nodes are system functions and gateways. The branches are the flows of inputs and outputs from system functions and gateways”

### 7.3.2 Property — Product

KFL notation for product:

:Prop Product

:Inst Type

:sup Role

:rem “a role played by an entity (physical product) or service (actor) or some combination of both that is developed to be sold”

### 7.3.3 Property — PhysicalProduct

:Prop PhysicalProduct

:Inst Type

:sup 2DSCtx.Product

:rem "A Physical Product is an Entity that is developed to be sold.

### 7.3.4 Property — Physical product with service

KFL notation for product service:

:Prop PhysicalProductWithService

:Inst Type

:sup Role

:sup 2DSCtx.PhysicalProduct

: rem “a physical product that incorporates a service”

### 7.3.5 Property — Service

KFL notation for service product:

:Prop Service

:Inst Type

:sup Actor

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:rem “activity sold as a product”

### 7.3.6 Property — Service using physical product

:Prop ServiceUsingPhysicalProduct

:Inst ActorType

:sup Actor

:rem "A service that utilizes a physical product."

### 7.3.7 Propery — Prototype

:Prop Prototype

:Inst Type

:sup Material

:name "Prototype"

:rem "Pre-production model of a product."

### 7.3.8 Property — Organization function

KFL notation for organization function:

:Prop OrganizationFunction

:Inst Type

:sup SystemFunction

:rem “The key function(s) that an enterprise provides”

(disjointSubProps OrganizationFunction)

### 7.3.9 Property — Facility function

KFL notation for facility function:

:Prop FacilityFunction

:Inst Type

:sup SystemFunction

:rem “a system that performs one or more specific activities by the provision of resources in a given global location”

(disjointSubProps FacilityFunction)

### 7.3.10 Property — Actor type

;;;metaproperty - needed to refer to types of actor in the ontology

:Prop ActorType

:Inst MetaProperty

:sup Type


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:name "Type of the Actor"

:metaPropFor Actor

### 7.3.11 Property — Actor

KFL notation for actor:

:Prop Actor

:Inst Type

:sup Role

:rem “actor is a role which is played by a systemfunction”

(disjointSubProps Actor)

### 7.3.12 Property — Customer

KFL notation for customer:

:Prop Customer

:Inst ActorType

:sup Actor

:rem “organization or person that receives a product”

### 7.3.13 Property — Supplier

KFL notation for supplier:

:Prop Supplier

:Inst ActorType

:sup Actor

:rem “facility in an organization that enters into an agreement with the acquirer for the supply of a product“

### 7.3.14 Property — Gateway

KFL notation for gateway:

:Prop Gateway

:Inst Type

:sup Basic

:rem "Gateways are used to control how Sequence Flows interact as they converge and diverge within a network "

### 7.3.15 Property — Diverging gateway

KFL notation for diverging gateway:

:Prop DivergingGateway

:Inst Type

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:sup Gateway

:rem " A diverging gateway has only one input and two or more outputs (describes an opening AND or a fork)"

### 7.3.16 Property — Converging gateway

KFL notation for converging gateway:

:Prop ConvergingGateway

:Inst Type

:sup Gateway

:rem "A converging gateway has two or more inputs and only one output (describes a closing AND or a join)"

### 7.3.17 Property — Inclusive diverging gateway

KFL notation for inclusive diverging gateway:

:Prop InclusiveDivergingGateway

:Inst Type

:sup DivergingGateway

:rem "A inclusive diverging gateway (opening OR) has one input and two or more outputs. An output shall have a condition (a Boolean)".

### 7.3.18 Property — Inclusive converging gateway

KFL notation for inclusive converging gateway:

:Prop InclusiveConvergingGateway

:Inst Type

:sup ConvergingGateway

:rem " An inclusive converging gateway (“closing OR”) has one default output and two or more inputs. An input shall have a condition (a Boolean). "

### 7.3.19 Property — Exclusive diverging gateway

KFL notation for exclusive diverging gateway:

:Prop ExclusiveDivergingGateway

:Inst Type

:sup InclusiveDivergingGateway

:rem "An exclusive diverging gateway (“opening XOR”, branch) inherits from an inclusive diverging gateway. The value of the condition of an output shall not be identical to the value of the condition of any of the other outputs of the XOR gateway (i.e. only one condition within the XOR gateway can be activated, so only one branch can be taken)."

### 7.3.20 Property — Exclusive converging gateway

KFL notation for exclusive converging gateway:


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:Prop ExclusiveConvergingGateway

:Inst Type

:sup ExclusiveDivergingGateway

:rem "An exclusive converging gateway ("closing XOR", merge) inherits from an inclusive diverging gateway. The value of the condition of an input shall not be identical to the value of the condition of any of the other inputs of the XOR gateway (i.e. only one condition within the XOR gateway can be activated, so only one incoming flow is needed)."

### 7.3.21 Property — Condition

KFL notation for condition:

:Prop Condition

:Inst Type

:sup MLO.Object

:rem "Boolean value as a result of a condition. "

### 7.3.22 Property — Business event

KFL notation for business event:

:Prop BusinessEvent

:Inst Type

:sup Basic

:rem "Event that occurs in the business domain."

### 7.3.23 Property — Start event

KFL notation for start event:

:Prop StartEvent

:Inst Type

:sup BusinessEvent

:rem "Start of a process sequence."

### 7.3.24 Property — End event

KFL notation for end event:

:Prop EndEvent

:Inst Type

:sup BusinessEvent

:rem "End of a process sequence."

### 7.3.25 Property — Decision event

KFL notation for decision event:

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:Prop DecisionEvent

:Inst Type

:sup BusinessEvent

:rem "An event where decisions are made or taken."

### 7.3.26 Property — Plan

KFL notation for project:

:Prop Plan

:Inst Type

:sup Information

:sup MLO.Object

:name "Plan"

:rem "Account of intended future course of action aimed at achieving specific goal(s) or objective(s) within a specific timeframe”

### 7.3.27 Property — Project

KFL notation for project:

:Prop Project

:Inst Type

:sup SystemFunction

:name "Project"

:rem “A planned undertaking with specified targets”

### 7.3.28 Property — Location

KFL notation for location:

:Prop Location

:Inst Type

:sup Information

:sup MLO.Object

:name "Location"

:rem "A site or position"

### 7.3.29 Property — Zonetype

KFL notation for zonetype:

:Prop ZoneType

:Inst MetaProperty


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