Characterizing IOF Terms with the DOLCE and UFO Ontologies

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Abstract. This paper is an ontological analysis exercise aiming, first of all, at clarifying the intended semantic of a number of general terms used in the manufacturing domain, selected by the Industrial Ontologies Foundry (IOF) initiative. In addition, we show how the DOLCE foundational ontology is well-suited as main reference framework for this task, integrated (in a few specific cases) with more recent work done in the framework of UFO. For each term, we propose a DOLCE-based (first-order) axiomatization together with examples and counter-examples. In several cases, some new primitives are introduced in addition to those used in DOLCE.

Keywords. Manufacturing, IOF, DOLCE, UFO.

1. Introduction

It is more than thirty years that ontologies are applied for knowledge representation or data management across engineering, e.g., in design or manufacturing [21]. The Industrial Ontologies Foundry (IOF)[2] has recently emerged as international effort to develop and promote a library of reference ontologies for these domains. One of the guiding ideas behind the IOF is that multiple data sources or information systems have a higher chance of interoperating if based on the same ontologies and, in particular, on the same upper-level ontology.

The work presented in the paper is an ontological analysis exercise aimed at clarifying the intended semantics of (some of) the most general terms identified in the scope of the IOF. The latter have been extracted (by a IOF team) from use-cases proposed by the IOF community to identify engineering modeling needs and, therefore, to support the development of ontologies based on community requirements. The terms we consider are: Plan, Manufacturing process plan, Manufacturing resource, Material resource, Instrumental resource, Assembly, Component, Planned process, Business process, Manufacturing process, Assembly process, Transport process, Manufacturing machine, Equip-

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[2]`https://www.industrialontologies.org/`, last accessed June 2019.

ment, Product, Product quality, Design, Feature description, Supplier, and Customer. Others IOF terms are left out because of their unclear intended meaning at the time in which this study is carried out.

For the purposes of the analysis we rely on the Descriptive Ontology for Linguistic and Cognitive Engineering (DOLCE) [13] integrated—in a few specific cases—with work done by the first author in the framework of the Unified Foundational Ontology (UFO) [10], and by work done by the second author in manufacturing [20,19,18].

We will rely on the classic version of DOLCE described in the final deliverable of the WonderWeb project [13]. Despite some of its basic choices have been slightly revisited in further work [3], and several drastic simplifications have been proposed (e.g., [17]), the classic version of DOLCE has remained stable since 2003. Remarkably, a proof of consistency was published in 2011 [12]. DOLCE and OntoClean [9] have also been used as the main inspiration to develop UFO [10].

In the following sections, the IOF informal definition is reported for each term, followed by the proposed DOLCE-based axiomatization together with examples and counter-examples. Some required extensions to DOLCE that are not specific to IOF terms are discussed in the final section although only in a preliminary setting.

From a formal perspective, we rely on plain first-order logic (FOL); formulas with free variables are meant to be universally quantified. Note also that in DOLCE most properties and relations involving endurants are assumed to be temporally indexed. However, we will sometimes omit the temporal index for the sake of simplicity, assuming that, if the property ϕ is time-indexed, $\phi(x)$ means that $\phi(x,t)$ holds ad the present time. For ease of understanding, DOLCE predicates have been renamed using non-abbreviated names if possible. A mapping table is reported in the appendix. The DOLCE taxonomy appears in Figure 1.

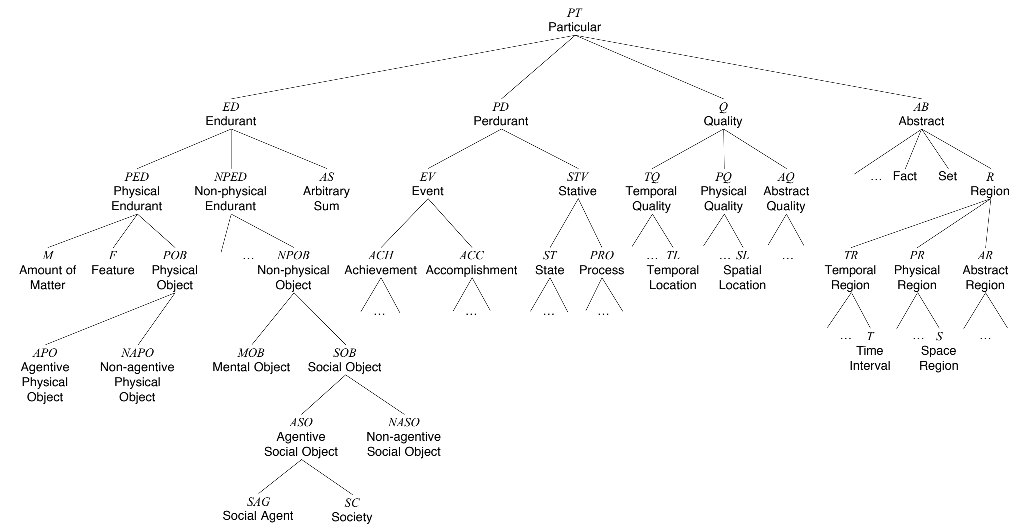

Figure 1. Taxonomy of DOLCE [13]

2. Plan and Goal

2.1. Plan

IOF informal definition: A plan is a document that prescribes a collection of related activities that achieve some organizational goal.[3]

We base our analysis on the notion of *description*. Descriptions are *information entities* about things that either exist at the present time or are just desired. Plans, goals, and designs will be considered as descriptions of a certain kind.

Let us first introduce some informal definitions:

(1) A *goal* is a *description* (more exactly, a *specification*[4]) of a generic desired state (i.e., the description of a *state kind*). A goal may be encoded in an agent's memory or in an information bearer like a computer file. In the latter case, the goal may endure after the occurrence of the perdurant it describes is not desired anymore (a goal is only historically dependent on an agent's mind).[5]

(2) A *plan* for a certain goal is a description of a generic perdurant (a kind of DOLCE Accomplishment)[6] such that there exists an agent who believes that any perdurant of such kind may cause the satisfaction of the goal.

(3) A perdurant that satisfies a plan is said to *realize* the plan. A plan may constrain its realizations in various ways. For example, it may constrain the internal structure of the realizing event, its participants, etc.

Note that a plan for a certain goal may be *wrong* (although an agent may believe it works). A *correct* plan for a goal is a plan whose realization always causes the goal satisfaction.

Examples: A set of instructions for manufacturing a product (e.g., a car) with the desired qualities.
Counter-examples: an arbitrary set of instructions which have no goal.

Formal account:

(A1) $goalForAgent(x,y) \rightarrow Spec(x) \wedge Agent(y) \wedge \forall z(sat(z,x) \rightarrow State(z) \wedge desires(y,z))$

(D1) $Goal(x) \triangleq \exists y(goalForAgent(x,y))$

(D2) $plan(x,g) \triangleq Spec(x) \wedge Goal(g) \wedge \forall y(sat(y,x) \rightarrow Accompl(y)) \wedge \exists w(Agent(w) \wedge ascribesGoal(w,x,g))$

(D3) $Plan(x) \triangleq \exists g(plan(x,g))$

(D4) $realizes(x,y) \triangleq Perdurant(x) \wedge Plan(y) \wedge sat(x,y)$

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[3] IOF terms definitions are not documented in a publicly available document.

[4] A specification is a description of a desired entity. See discussion in Section 8.

[5] Properly speaking, a goal is something in an agent's mind, which may be represented as a *mode* (a mental attitude) inhering in the agent. The description we are talking of would be then the *(propositional) content* of a goal, not a goal in itself. For our purposes, we *objectify* goals identifying them with their content. In this way, instead of being *specifically dependent* on an agent's mind, a goal turns out to be just historically dependent on it. The same approach has been adopted for plans, which are identified with their descriptional content.

[6] Within *eventive* perdurants (i.e., perdurants that are not states nor processes), DOLCE distinguishes between *achievements*, which are atomic, and *accomplishments*, which are non-atomic.

(D5) $endorses(x,y) \triangleq Agent(x) \land Plan(y) \land \exists g(goalForAgent(g,x) \land ascribesGoal(x,y,g))$

According to (A1), if an agent has a goal, then it desires any of the states described by the goal. The *sat* predicate, standing for *satisfies*, is discussed in Section 10.1, whereas *Spec*, read as 'specification', is presented in Section 8.1. Multiple agents may share the same goal. According to (D5), an agent *endorses* a plan if one of the agent's goals is ascribed to the plan. Notice that an agent may endorse several alternative plans for the same goal. Endorsing a plan does not mean intending to realize the plan.

2.2. Business Process Plan

This term is not present in the ones originally taken into account by the IOF. We believe it is however useful as a general category for more specific classes related to engineering. We simply define a *business process plan* as a plan that is endorsed by an organization; see (D6) where *Org* is a primitive predicate standing for 'organization'.

(D6) $BusinessProcessPlan(x) \triangleq Plan(x) \land \exists y(Org(y) \land endorses(y,x))$

2.3. Manufacturing Process Plan

IOF informal definition: A *Manufacturing process plan* is a specification that prescribes the collection of related activities in a manufacturing process that produces a product with the desired qualities.

Our informal definition is as follows:

(4) A *Manufacturing Process Plan* is a *Business Process Plan* whose goal is the production of a *Physical object* with certain qualities.

Formally,

(D7) $MfgProcessPlan(x) \triangleq BusinessProcessPlan(x) \land \exists g\ (plan(x,g) \land \forall v(sat(v,g) \rightarrow \exists w(beginsLife(v,w))))$

(D8) $beginsLife(x,y) \triangleq Perdurant(x) \land (PhysObj(y) \lor M(y)) \land participates(y,x) \land \forall t(pre(x,t) \rightarrow pre(y,t)) \land \exists z(meets(z,x) \land \forall t(pre(z,t) \rightarrow \neg pre(y,t)))$

These definitions rely on the DOLCE notions of *perdurant*, *participation*, and *presence in time*. According to (D7), a *Manufacturing process plan* is a *Business plan* whose goal is satisfied by the appearance of a new physical object or amount of matter. Such appearance is modelled by means of (D8).[7] Accordingly, a perdurant x *begins the life* of y iff it is such that y is constantly participating to x, and there exists a perdurant z, when y is not present, that immediately precedes x. Intuitively, $beginsLife$ models therefore the perdurant x that is the beginning of an object's y life, so that y is not present at those perdurants preceding x. The definition may be strengthen by explicitly modeling specific goal classes, e.g., for the creation or modification of technical artifacts.

[7] (D8) uses Allen's *meets* relation between perdurants (x meets y iff x precedes y and is temporally connected to y).

3. Resources

3.1. Manufacturing Resource

IOF informal definition: A resource is any person or thing that adds value to a product in its creation, production, or delivery (APICS).

We shall base our analysis on the following dictionary definition:

> "The resources of an organization or person are the materials, money, and other things that they have and can use in order to function properly" (Collins dictionary).

The fact that resources need to be actually *accessible* to an agent (i.e., to be under its control) is crucial [19].[8] This means the notion of resource is a *relative* one: something is a resource for somebody and for a purpose. In an industrial context, we interpret the APICS definition assuming that such purpose is the participation to a relevant value-adding process (i.e., a Business Process). So, a first informal definition is as follows:

(5) For a given *Agent*, a *Manufacturing Resource* is an entity which is *controlled* by such *Agent* and *may participate* to a *Manufacturing Process owned* by such *Agent*.

We therefore assume that a physical object or an amount of matter is *controlled* by an agent if it is in the *possession* of such agent, while a person is controlled by an agent if some kind of *subordination* relation holds with respect to such agent. Care is needed to account for the notion of 'may participate'. Considering a predicate like $MayParticipate(x,y)$, where x is a resource and y a process, it is clear that it has an intended *modal* meaning and y is a *possible* (future) process which is only *meant to* occur.

To get rid of modality, we model manufacturing resources in relation to *plans*. Hence, something is a resource *for a particular agent's plan*. Accordingly, we refine (5) as:

(6) For a given *Agent* that *endorses* a certain *Manufacturing Process Plan*, a *Manufacturing Resource* for such plan is an entity that is *controlled* by the *Agent* and *satisfies* the description of a participant in the plan.

Examples: a single screw present in the workshop (even as part of a product intended to be sold); the amount of metal that constitutes such screw, assuming it may be needed (even in melted form) in a process; a screwdriver present in the workshop;
Counter-examples: a component which is needed but is neither present in the workshop, nor described in the corresponding process plan; a product which is present in the workshop (not sold yet) but cannot be used for a manufacturing process. Importantly, entities that are not described as plan participants are not manufacturing resources. E.g., an amount of material stored in a company's garage is not a manufacturing resource if it is not associated to a process plan. Finally, time is not considered as a resource.
Terminological issues: the emphasis on value emerging from the APICS definition seems to be restrictive. A single screw may be considered as a resource for building an artifact, but it would be hardly considered as adding value. Moreover, we suggest

[8] An *accessible* resource may be not *available* for a particular task (for example because it is allocated to another task), so accessibility is different from availability.

to introduce a generic notion of resource, as something that may participate to non-manufacturing processes, such as transportation processes or other business processes.

Formulas below define manufacturing resources.

(D9) $mfgResource(r,x,y) \triangleq controls(x,r) \wedge MfgProcessPlan(y) \wedge endorses(x,y) \wedge \exists z(participantDescr(z,y) \wedge sat(r,z))$

(D10) $participantDescr(x,y) \triangleq Descr(x) \wedge Plan(y) \wedge pPartOf(x,y) \wedge \forall z(sat(z,y) \rightarrow \exists wt(participates(w,z,t) \wedge sat(w,x)))$

(D11) $MfgResource(r) \triangleq \exists xy(mfgResource(r,x,y))$

Definition (D9) defines a manufacturing resource *r* of an agent *x* that endorses a plan *y* as something which is controlled by *x* and satisfies the description of a participant in the realization of *y*. In turn, a participant description is defined by (D10) as a description that is part of the plan and such that whatever realizes the plan has as a participant something that satisfies such description. Altogether, these definitions convey the idea that manufacturing resources *may* participate in a manufacturing process, but they do not *necessarily* participate to it. In addition, it is worth stressing that according to this view it is possible to consider an entity as a manufacturing resource only in the light of a manufacturing process plan where the resource is (at some extent) described. This rules out those entities that may be accidentally used during a manufacturing process, e.g., tools whose use was not expected by process planners. Although this perspective seems restrictive at first glance, it makes sense in our understanding of the fact that resources are carefully selected during planning phases according to their availability, capabilities, or capacities, among other requirements. A proposal to be further analyzed and tested against experts' knowledge is to distinguish between *planned* and *unplanned* resources, where – differently from the former – the latter can be selected on the fly depending on specific and perhaps even unattended happenings on manufacturing shop-floors.

Finally, the definitions above rely on several notions discussed elsewhere. *Endorses* holds between agents and plans (Section 2.1); *sat* holds between entities and their description (Section 10.1); *controls* is a primitive between agents and other entities.

3.2. Material Resource

IOF informal definition: A *material resource* is any substance from which a product can be made. Explanation: A material substance is often referred to as raw material in the context of a manufacturing process (IOF: Material resource. Possible synonyms: material, input resource. Former term: material substance")

We propose the following informal definition:

(7) A *Material Resource* is a *Manufacturing Resource* such that, if it participates to a manufacturing process, at least parts of it are present in the intended final product (other parts—e.g., cutoffs—may be wasted).

Examples: an amount of clay that is used during a manufacturing process to create a vase, so that at the end of the process at least part of it *constitutes* the vase; a plank of wood that is used in a process to create a table, so that at the end of the process some part of the plank is part of the table (note that in this case the amount of wood constituting the

plank is also a material resource); a screw that is used during a manufacturing process to create a table, so that at the end of the process the screw is part of the table.
Counter-examples: the machines, tools, fixtures, gasoline, lubricants used during manufacturing processes.
Terminological comment: We are considering here those resources which are usually listed in a *bill of materials*. This does not usually include the machines needed for the manufacturing process, nor the fuels or lubricants used for their functioning, nor the people needed to control these machines.

Let us first define the *intended output* of a process that realizes a manufacturing process plan as an entity whose coming into being satisfies the goal of the plan:

(D12) $$intendedOutput(x,y) \triangleq \exists pgz(MfgProcessPlan(p) \land realizes(y,p) \land plan(p,g) \land sat(z,g) \land beginsLife(z,x))$$

We then define material resource as follows:

(D13) $$materialResource(r,x,p) \triangleq mfgResource(r,x,p) \land \forall yt(realizes(y,p) \land participates(r,y,t) \rightarrow \exists zst'(intendedOutput(z,y) \land partOf(s,r,t) \land includedIn(s,z,t') \land t \prec t'))$$

(D14) $$includedIn(x,y,t) \triangleq partOf(x,y,t) \lor \exists z(const(z,y,t) \land partOf(x,z,t))$$

(D15) $$MaterialResource(r) \triangleq \exists xp(materialResource(r,x,p))$$

According to (D13), a material resource is a manufacturing resource such that, if it participates to a manufacturing process, part of it is included in the intended result of such process. According to (D14), an endurant is included in another endurant if it is part of it or is part of its constituent.

3.3. Instrumental Resource

This term is not included in the original IOF terms list. The rationale for this new term is to complete the description of the different kinds of participants in a manufacturing process, distinguishing the process input (*material resources*), the process output (*intended output*), and the resources needed to realize the process (*instrumental resources*) [19,21].

Similarly to all resources, instrumental resources are relative to a particular process plan. For example, a certain machine could be instrumental for a manufacturing process and just input for a maintenance process.[9]

(8) An *Instrumental Resource* is a *Manufacturing Resource* such that, if it participates to a *Manufacturing Process*, none of its parts will be included in the intended output of such process.

Examples: manufacturing machines, tools, fixtures, gigs, oils, lubricants (when not used as input of a manufacturing process);
Counter-examples: components and amounts of matter used as input of manufacturing process.

The formal definition is analogous to that of *material resource*:

[9] Recall that we have only defined a particular kind of input resources, namely material resources. A more general notion of (input) resource may be useful.

(D16) $instrumentalResource(r,x,p) \triangleq mfgResource(r,x,p) \wedge$
$$\forall yt(realizes(y,p) \wedge participates(r,y,t) \rightarrow \neg \exists zst'(intendedOutput(z,y) \wedge \wedge partOf(s,r,t) \wedge includedIn(s,z,t') \wedge t \prec t'))$$

(D17) $InstrumentalResource(r) \triangleq \exists xp(instrumentalResource(r,x,p))$

The notion of instrumental resource may be specialized to cover the distinction between resources like (i) machines or tools, (ii) fixtures or gauges, (iii) oils or lubricants, where (i) 'execute' the desired task (e.g., create a hole), (ii) 'support' tasks execution, and (iii) allow for the proper functioning of (i) and (ii).

4. Assemblies and Components

4.1. Assembly

IOF informal definition: An assembly is a combination of parts and components that form a functional entity.

The IOF informal definition relies on a notion of *functional unity*. We believe however that a different notion of unity is required. Consider for example a TV monitor and its remote controller, both on the same desk, but not touching each other. How many assemblies are on the desk? People say two, not one. Yet, the monitor and the remote controller form a functional entity. Our conclusion is that we should introduce a different notion of unity, which has a *topological* nature, since it is based on spatial connection. Broadly speaking, assemblies are *topological wholes* like all physical objects, except that they are formed of physical objects bound together by a relation of *weak spatial connection* [2]. Informally, we shall say that two physical objects are weakly connected if they are just in touch one each other, and they maintain their own unity. On other hand, an example of strong connection is the one existing between any two parts of a physical object that together constitute the object itself. So, weak connection stands for contact, while strong connection stands for intimate material connection. Typically, mechanical assemblies are maximally weakly-self-connected, while their basic components are maximally strongly-self-connected.[10]

Such a connection may be mechanically implemented in various ways: in simple cases we may have simple contact (e.g., a tower of wooden blocks), in other cases various forms of mechanical joints or fastenings may be adopted. Our informal definition is therefore as follows:

(9) An *Assembly* is a *Technical Artifact* constituted by the mereological sum of two or more physical objects that are weakly spatially connected one each other.

This definition constrains assemblies to be technical artifacts.[11] Otherwise, any pile of stones would count as an assembly. Relying on (D12), we define technical artefacts as:

[10] We shall not consider welded or glued assemblies here. They would deserve a more specific approach since the topological unity of their components may be destroyed by the welding process.

[11] The notion of technical artifact is commonly introduced to explicitly talk of functional artifacts distinguishing them from artifacts created, e.g., for pure aesthetic purposes like objects of art [1].

(10) A *technical artifact* is an entity that is/was the *intended output* of a *manufacturing process*.

Note that (9) assumes that an assembly does not just *coincide* with a sum of weakly connected physical objects, but rather it is *constituted* by such a sum. This because the identity criterion of the assembly and that of the sum are kept separate. For example, the assembly may survive the replacement of a component, while the sum of components that constitutes it is a different one if a component is replaced.

Finally, (9) implicitly relies on the assumption that a physical object may keep its nature of physical object when it is connected with another physical object. This is not always the case: for example, when two drops of water are connected, they loose their nature of physical objects, and a new physical object comes into being. Assuming that the components of an assembly count as physical objects means assuming that their unity is not destroyed by the various mechanical joints described above.

We rely here on the DOLCE notion of *physical object*, according to which a physical object is a physical endurant with *some* kind of unity. In particular, we assume that the unifying relation is a generalized topological connection, which can be either *weak* or *strong*

Examples: A pile of blocks; a TV monitor; a TV remote controller; a stonewall. **Counter-examples:** The sum of a TV monitor and its remote controller (assuming they are not touching each other); a disassembled bike; a heap of stones (arranged in a casual way).

Formally:

(D18) $$Assembly(x) \triangleq TechArtifact(x) \wedge \forall t(pre(x,t) \rightarrow \exists wyz(dConst(w,x,t) \wedge pre(w,t) \wedge w = y + z \wedge PhysObj(y) \wedge PhysObj(z) \wedge wConn(y,z,t)))$$

(D19) $$TechArtifact(x) \triangleq PhysOb(x) \wedge \exists y\ (intendedOutput(x,y))$$

In the formula above, $pre(x,t)$ and $dConst(x,y,t)$ are DOLCE relations standing respectively for presence in time and *direct constitution*. Definition (D18) says that an assembly is a technical artifact such that, whenever it is present, something that directly constitutes it is also present, and is the mereological sum of two objects that are weakly connected one each other.

4.2. Component and Component Part

IOF informal definition: A *component* is a part or subassembly that goes into a higher level assembly or the final product (adapted from APICS). Explanation: A particular artifact can be considered as a component or an assembly depending on the context of a manufacturing process.

To account for this notion, we first introduce a distinction between those components that are proper parts of assemblies (which will be therefore *component parts* of such assemblies) and those that simply *may* be parts (perhaps because they are designed to be parts), but are not necessarily actual parts. We define the *component part* relation as:

(D20) $$componentPart(x,y) \triangleq pPartOf(x,y) \wedge PhysObj(x) \wedge PhysObj(y)$$

This reflects the idea that a component part is a special kind of part, namely a part that can be recognized as a physical object in itself and has therefore its own *unity*. Each part of a physical object which is a physical object in itself can be considered as a *component part* of that object. We can now informally define the general notion component as follows:

(11) A component is a physical object that satisfies the description of a proper component part of an assembly within a design specification.

Formally,

(D21) $Component(x) \triangleq \exists yz(DesignSpec(y) \wedge pPartOf(z,y) \wedge sat(x,z))$

By looking at the definition, the *DesignSpec* predicate is introduced in Section 8.1 and stands for the description of a desired entity.

Example: the engine of a car (component and component part);
Counter-example: a car engine that is not installed in any car (component but not component part); a bulb that is accidentally installed in a lamp (component part but not component).

5. Processes

5.1. Planned Process

IOF informal definition: The term is present but not defined in the IOF list.

We define a planned process as a process that is the realization of a plan. Such a realization is a DOLCE *accomplishment*, so:

(12) A *Planned Process* is an *Accomplishment* that realizes a *Plan*.

Example: A manufacturing process for the creation of a table;
Counter-example: John's (unplanned) walking from location A to B.

Formally, definition (D22) relies on (D4).

(D22) $PlannedProcess(x) \triangleq Accompl(x) \wedge \exists y\ (realizes(x,y))$

5.2. Business process

IOF informal definition: A *business process* is a structured set of activities performed to achieve an organizational objective.

Our informal definition is as follows:

(13) A *Business process* is an *Accomplishment* that realizes a Business Process Plan (see (D8)).

Example: any complete realization of a business process plan.
Counter-example: a series of action which is only a partial realization of a business process plan.

(D23) $BusinessProcess(x) \triangleq Accompl(x) \wedge \exists y\ (realizes(x,y) \wedge BusinessProcessPlan(y))$

5.3. Manufacturing Process

IOF informal definition: A manufacturing process is a structured set of activities performed to produce a good or service.

Our refined definition:

(14) A *manufacturing process* is a process that is the realization of a Manufacturing Process Plan.

Formally,

(D24) $MfgProcess(x) \triangleq Accompl(x) \wedge \exists y(realizes(x,y) \wedge MfgProcessPlan(y))$

5.4. Assembly Process

IOF informal definition: An *assembly process* is a type of manufacturing process that combines two or more components into a single parent assembly or final product.

Our refined definition:

(15) An *assembly process* is a *manufacturing process* whose *intended output* is an *assembly*.

Formally:

(D25) $AssemblyProcess(x) \triangleq MfgProcess(x) \wedge \exists y(intendedOutput(y,x) \wedge Assembly(y))$

5.5. Transport Process

IOF informal definition: A transport process is a process that involves the movement or change in location of some raw material, component or product by some agent or mechanism.

Our refined definition:

(16) A *transport process* is the realization of a plan whose goal is the change of location of a physical object.

Formally:

(D26) $TransportProcess(x) \triangleq BusinessProcess(x) \wedge \exists pg(realizes(x,p) \wedge plan(p,g) \wedge \forall y(sat(y,g) \rightarrow LocationChange(y)))$

LocationChange is taken as a primitive for the sake of simplicity.

6. Machine and Equipment

6.1. Manufacturing Machine

IOF informal definition: A machine is a mechanical system designed expressly to perform a specific task, such as the forming of material or the transference and transformation of motion, force or energy (ISO 22096:2007).

The IOF definition refers to the general notion of machine adopted in mechanics, according to which any physical object that may be used to transmit/convert/generate motion, force, or energy would count as a machine. A lever, a wheel or a pulley are examples of machines. For our purposes we simply characterize a manufacturing machine as an assembly which may be instrumental in a manufacturing process and is therefore an instrumental resource:

(A2) $MfgMachine(x) \rightarrow Assembly(x) \wedge InstrumentalResource(x)$

Admittedly, this definition only weakly captures the manufacturing understanding of machines. Future work to improve the ontological representation of machines is needed.

Examples: a drilling machine, an (assembled) bench used as support for certain operations.
Counter-examples: a lever, a pulley, an amount of fuel used in a process.

6.2. Equipment

IOF informal definition: Manufacturing equipment is equipment which is operated for directly producing a product, in a manufacturing process (ISO 20140-1:2013).

The term ‘equipment’ in English denotes a plural entity: “the set of necessary tools, clothing ecc. for a particular purpose” (Cambridge English Dictionary). This is clearly different from ‘piece of equipment’.

Assuming that the IOF (and ISO) definition reported above refers to a plural entity, the emphasis on *directly* producing a product deserves attention. Is, e.g., a forklift used to move materials around in the factory or to the production line an equipment? The forklift is not *directly* producing the product but is certainly *indirectly* necessary to supply heavy materials to the production line.

Our informal definition is therefore as follows:

(17) An *equipment* is a maximal collection of manufacturing resources that may be allocated to a manufacturing process.

If this informal definition is accepted, some further work is done to formally characterize it. The idea is that, if several duplicates of a certain resource are available, only one of them may be allocated to a certain process, becoming therefore a piece of equipment for such process.

7. Product and Product Qualities

7.1. Product

IOF informal definition: A product is the tangible outcome of a process (ISO 6707-3:2017). A product is often produced for sale, barter, or internal use, etc.

The IOF informal definition underlines two aspects of a product: its economic relevance and the fact that it is the outcome of a process. To better clarify the former, we think it is useful to first clarify the notion of *good*:

(18) A *good* is a (tangible or intangible) object that has an economic value, over which ownership rights can be established and whose ownership can be transferred from one agent to another.

Note that, according to [11], the possibility of transferring their ownership is what distinguishes goods from services: goods are transactable and transferrable, while services are transactable but not transferrable (the purpose of the transaction is not a transfer of ownership).

Not all goods are products, however. In particular, real estates are not usually considered as products. A well-founded account of the notions of good, service, and product (including financial products) requires therefore some further work. For our purposes, we focus on *manufacturing products*, suggesting the following informal definition:

(19) A *manufacturing product* is an amount or matter or a physical object that is/was intended to be sold, and is the intended output of a manufacturing process.

Examples: a car; some sieved gravel; some crude oil extracted from sea; some sawdust properly collected in order to be sold.
Counter-examples: a tool produced by a company for internal purposes and not intended to be sold. Some sparse sawdust not intended to be sold.

Formally, we define a manufacturing product as follows:

(D27) $$MfgProduct(x) \triangleq \exists yp\ (intendedOutput(x,y) \land Plan(p) \land \forall z(realizes(z,p) \rightarrow Selling(z) \land theme(x,z)))$$

By the definition above, a product is the intended output of a manufacturing process such that there exists a plan of selling it. We rely here on a *Selling* primitive, which classifies those events that are selling actions, and a *thematic role*[12] relation, which says that x is the *theme* of such actions.

7.2. Product Quality

IOF informal definition: A physical or functional characteristic of a product that can be measured or qualitatively evaluated. (Source: Adopted principly from ISO 9000:2016)

The above definition is in line with the DOLCE notion of *individual quality*. Individual qualities (qualities for short) may be seen as specific aspects of things we use to compare them. They *inhere* in things, where inherence is a special kind of existential dependence relation, which is irreflexive, asymmetric, anti-transitive, and functional. They are directly *comparable*, while objects and perdurants can be compared only with respect to a certain quality kind (e.g., to compare physical objects, one resorts to the comparison of their shapes, sizes, weights, and so on). Qualities are distinct from their values (a.k.a. qualia), which are abstract entities representing what exactly resembling qualities have in common, and are organized in spaces called quality spaces; each quality kind has its own quality space. For instance, weight is a quality kind, whose qualia form a linear quality space. Note that DOLCE qualities are directly comparable but not necessarily

[12] Thematic roles are ways of participating to an event, typically corresponding to the semantic arguments of a verb.

measurable: for instance, it may make sense to say that a product is more beautiful or more reliable than another even without having a *metric* for beauty or reliability.

Based on this notion, we define product qualities as follows:

(20) A product quality is a specific aspect of a product which can be directly compared with similar aspects of another product.

Examples: The mass of a car, the shape of a bolt.
Counter-examples: The head of a bolt, the surface of a table, the specific redness of an apple (they are dependent entities like qualities, but they are not qualities).

Formally,

(D28) $ProdQuality(x) \triangleq Quality(x) \wedge \exists y\ (MfgProduct(y) \wedge inheres(x,y))$

Finally, note that the IOF definition of product quality covers functionalities, too. The latter have been extensively discussed in the literature and different ontologies have been proposed (e.g., [5,15]). The representation of functionalities in our framework is left to future work; the reader can refer to [4] for a DOLCE-based approach to model functionalities as qualities.

8. Design and Feature Specification

8.1. Design Specification

IOF informal definition: A design is a specification that describes a collection of features to be created for a product.

Let us compare the above definition with those of the following IOF terms:

- Feature description: *a description that details some distinctive characteristic about a product.*
- Quality specification: *a specification of some feature, input, processing, or output expected in a new product, a system, or satisfying some other organizational need, but without expressing the alternatives, technical details or how the requirment is to be met.*

First, the three terms seem to be strictly related. Second, they leave space for ambiguities. E.g., 'design' explicitly talks of 'features', but nothing is said on the intended meaning of the latter term, which is notoriously ambiguous [20]. On the other hand, 'feature description' refers to products' *characteristics*, but it is unclear how design and feature descriptions relate to each other. For example, is 'characteristic' more general than 'feature'? Finally, 'quality specification' is meant to provide – at a first glance – a generic description of the desired product without specifying any technical details.

For our axiomatization, we first extend the notion of Description (cf. Section 10.1) to explicitly cover specifications and then define design specifications as the most encompassing descriptions for a desired artifact:

(21) A *specification* is a description of a desired entity. It is historically dependent on the existence of an agent who desires the entity that the description describes.

(22) A *design specification* is the specification of a desired *artifact*. It specifies its qualities, features, components (including the assembly relations between them) functionalities, materials, etc.

Examples: a design specification describing a table (to be realized) made of wood and consisting of various components (legs, screws, etc.) assembled in a specific way.
Counter-examples: a process plan, a feature specification.

Formally:

(D29) $Spec(x) \triangleq Descr(x) \land \exists a(Agent(a) \land \forall y(sat(y,x) \rightarrow desires(a,y)))$

We can now characterize design specifications as follows:

(D30) $DesignSpec(x) \triangleq Spec(x) \land \forall y(sat(y,x) \rightarrow TechArtifact(y))$

For the definition of technical artefacts ($TechArtifact$), see Section 4.

8.2. Feature Specification

IOF informal definition: A feature description is a description that details some distinctive characteristic about a product.

In this definition, it is unclear what 'characteristics' are. In the analysis of this term done within the scope of BFO, the term 'feature description' is said to be " an umbrella term including quality, product quality of material entities or information entities, metalevel characteristics such as availability, reliability, average dimensions, and so forth of series or batches of material entities, as well as characteristics of processes such as rate, continuity and so forth".

In the light of the above considerations on specifications, we think that the term 'feature *specification*' is more appropriate. The following informal definition is proposed:

(23) A *Feature Specification* is a *Specification* that describes desired *Qualities* or (physical) *Features*. The latter are elements such as holes and protrusions, which are ontologically dependent physical objects.

Example: hole specification, protrusion specification, bump specification, specification of product's weight or height.
Counter-example: specification of product's component, plan.

Formally,

(D31) $FeatureSpec(x) \triangleq Spec(x) \land \forall y(sat(y,x) \rightarrow Feature(y) \lor Quality(y))$

Specific axioms for feature modeling can be introduced when needed (e.g., to specify that material features, differently from immaterial ones, are proper parts of their material hosts [18]).

9. Suppliers and Customers

9.1. Supplier

IOF informal definition: A provider of goods or services. Source: APICS (Revised: An organization or individual that sells or provides products or services to other organizations and individuals.)

We suggest to interpret the IOF definition in terms of the notion of *commitment*:

(24) A supplier is an agent who is publicly committed to sell some products or services.[13]

Example: A company that sells cars.
Counter-example: A private person who occasionally agrees selling his car.

The same approach can be in turn used to define customers.

9.2. Customer

IOF informal definition: A organization or person that buys or receives a good or service.

In our approach, customer is defined as follows:

(25) A customer is an agent who is publicly committed to buy some products or services.

Example: John buying a car.
Counter-example: John renting a car.

In DOLCE, commitments would be classified as *mental objects* existentially dependent on an agent. We prefer however to model commitments and other mental attitudes adopting the UFO approach [10], according to which mental attitudes are *externally dependent modes*, which inhere in agents and are existentially dependent on other things. We see UFO modes as a generalization of DOLCE qualities that, besides individual qualities, allow for *relational qualities*, which are qualities that, besides inhering in a certain entity, are existentially dependent on something else. For example, the love John has towards Mary is a relational quality inhering in John and existentially dependent on Mary.

This generalized account of qualities is crucial to model *reified relationships*, a.k.a. *relators* [6,7], which are mereological sums of qualities. In particular, to account for suppliers and customers we have to account for a *contractual relationship*, which regulates an *economic exchange* perdurant. As shown in Fig. 2, such a relationship is a sum of mutually dependent conditional commitments inhering in the provider and the receiver. In turn, commitments are externally dependent modes of a special kind, which cease to exist when an event that *fulfills* them occurs. So, in Fig. 2, a provider's *commitment to sell* is a mode inhering in the provider and existentially dependent on a reciprocal *com-*

[13] We suggest to reserve supplier for selling goods, and provider for selling services. Another possibility is to adopt the terms *good supplier* and *service supplier*.

mitment to buy inhering in the receiver. The former commitment is fulfilled by a sell perdurant, the latter commitment is fulfilled by a buy (cash) perdurant.

In the light of this analysis, we can define a supplier as an agent who has a commitment to sell, and a customer as an agent who has a commitment to buy.

(D32) $$Supplier(x) \triangleq Agent(x) \wedge \exists c(Commitment(c) \wedge inheres(c,x) \wedge \forall y(fulfills(y,c) \rightarrow Selling(y)))$$

(D33) $$Customer(x) \triangleq Agent(x) \wedge \exists c(Commitment(c) \wedge inheres(c,x) \wedge \forall y(fulfills(y,c) \rightarrow Buying(y)))$$

The definitions rely on the primitive relation *fulfills* (holding between a perdurant and a commitment), as well as on the *Selling* and *Buying* primitives. The formulas may be adjusted in order to characterize the commitments as *public* commitments (e.g., towards a target community of potential customers) or to specify the nature of the things sold.

We could also define a *prospective customer* as a person to whom a specific offering is addressed but may decide not to buy. In this case we would need to model the customer's *claims* towards the supplier [16].

10. Required Extensions and Adjustments to DOLCE

10.1. Descriptions and their Satisfaction

Descriptions are endurants that are not directly located in space and depend on a community of intentional agents. They are hereby understood as information content entities, e.g., the informative content of a business plan that is supported in multiple information carriers like digital files or printed materials. [14]

(A3) $$Descr(x) \rightarrow NonAgentiveSocialObject(x)$$

(A4) $$Descr(x) \wedge partOf(y,x) \rightarrow Descr(y)$$

(A5) $$sat(x,y,t) \rightarrow (PhysicalEndurant(x) \vee Quality(x)) \wedge Descr(y) \wedge TimeInterval(t)$$

(A6) $$sat(x,y) \rightarrow Perdurant(x) \wedge Descr(y)$$

The *sat* predicate models the compliance between a description and the 'realizing' entity; e.g., a technical artefact and a design specification. Two versions of this predicate are used, depending on the nature of the first argument: if it is an endurant or a quality, then a temporal index is introduced to capture the time at which compliance holds; e.g., a certain product may satisfy a given description at a time t but not at t'.

10.2. Physical Objects and Topological Connection

Physical objects are generically assumed in DOLCE as physical endurants with unity, but their exact kind of unity is not specified. For our purposes, we understand a physical object as a maximally self-connected amount of matter *of a certain kind*, or as a

[14]See [14] for the introduction of descriptions in the DOLCE framework. With respect to such paper, we assume here that a description describes just one concept, so that satisfying a description means being classified by the corresponding concept.

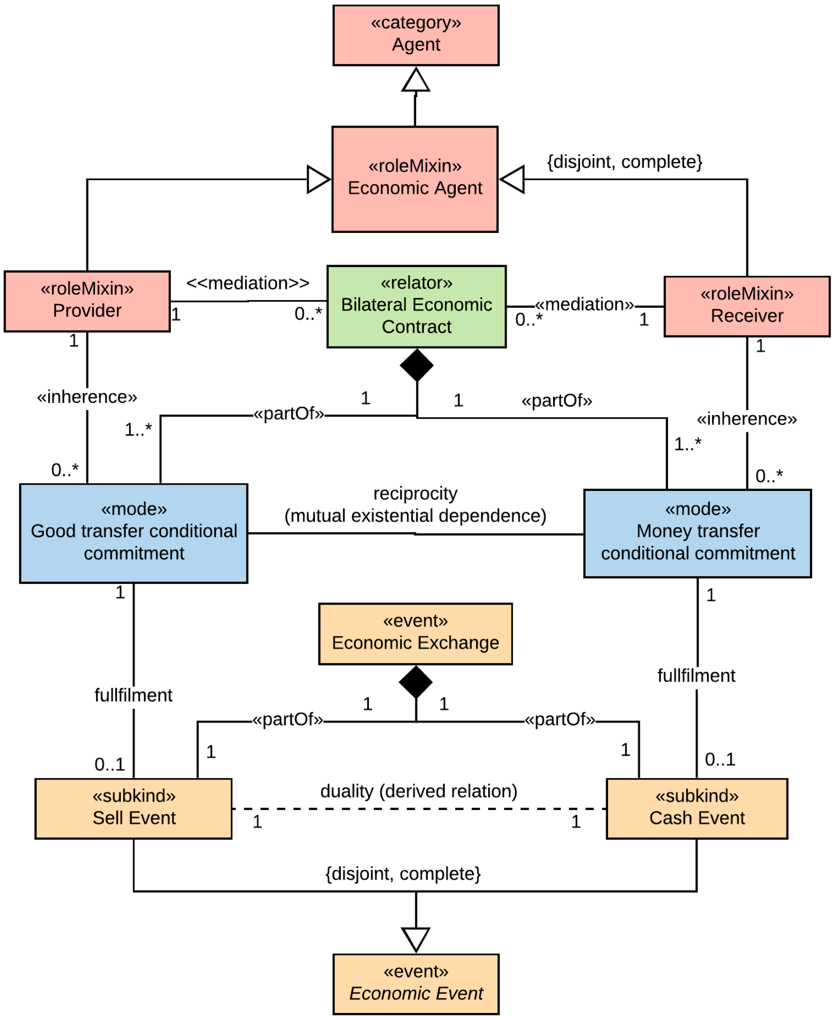

Figure 2. OntoUML modeling pattern for economic contracts [8]

connected sum of maximally connected amounts of matter of different kinds. So, a drop of water in a glass is a physical object, but if more water is poured the water originally constituting the drop does not constitute a physical object any more. A minimal formalization of connection is reported below. See [2] for an analysis of the difference between weak and strong connection.

(D34) $spatiallyConnected(x,y) \triangleq$
$$\exists l_1 l_2 (spatialLocation(l_1,x) \wedge spatialLocation(l_2,y) \wedge connected(l_1,l_2))$$

(A7) $connected(x,x)$

(A8) $connected(x,y) \rightarrow connected(y,x)$

11. Conclusion

We discussed across the paper how the DOLCE foundational ontology, used in tandem with UFO, can support knowledge representation for engineering and, in particular, for manufacturing modeling. Although the analysis aimed at discussing terms relevant in the context of the IOF, these capture general and basic notions. Hence, the value of the analysis is not restricted to the IOF and is applicable in manufacturing taken at large.

Providing a rigorous ontological framework for manufacturing proved challenging and, not surprisingly, further work is necessary. E.g., we implicitly relied on a number of notions belonging to the realm of *social ontology* such as *agent* or *organization*, as well as the idea that agents *control* resources or *endorse* plans to realize their goals. Further work is required to enhance the formal representation of these notions in a way that is functional for manufacturing modeling. Concerning the representation of resources, it may be useful to distinguish and characterize different resource classes depending on their role with respect to processes. Also, one should better characterize formal relations to explicitly capture the *availability* of resources or their *allocation* to perdurants.

Finally, recall that DOLCE (and UFO) is a foundational ontology, whose extension and application to manufacturing can be done in a number of different ways according to experts' and stakeholders' requirements. The material presented throughout the paper does not therefore show *the* way in which DOLCE *has* to be used for manufacturing. It rather shows a possible manner of extending it based on previous works and discussions with domain experts. Our exercise shows that the ontology is well suited for manufacturing representation. E.g., by means of the relation of *constitution* we can sharply distinguish between products and the materials out of which they are made, but also an assembly from its components. The first distinction is useful to classify materials and make sense of engineering parlance according to which a product is *made of* a certain material. In the second case, we can claim that (at least some of) the components forming an assembled product can be replaced without compromising the product's identity.

Concluding, we see on the one hand a growing interest in the manufacturing community (at both academia and industry) towards the use of ontologies. On the other hand, however, there is also a tendency towards representational approaches either based on poor modeling principles which only superficially capture the complexity of domain knowledge, or which attempt to reduce multiple viewpoints to a single *prescribing* model. Against the former tendency, domain experts and stakeholders should be aware that ontology development is as complex as any other engineering task. The better the ontology is, the higher are the chances of re-using it across systems for data organization, data sharing, or automated reasoning. The conceptual nuances of ontologies aim at making explicit the complexity of domain knowledge; they are not there for ontologists' riddles. Against the latter tendency, *monolithic* reference systems have probably better performances rather than *pluralistic* systems for practices like homogeneous data management. We hold, however, that ontologies must represent human knowledge by taking into account the commonalities and differences of multiple application contexts and knowledge systems. When these systems do not share the same view, forcing them to fit the same representational model is a high questionable choice.

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Appendix: DOLCE Predicates Abbreviations Table

Signature hereby used	**DOLCE predicate**	**Informal reading**
const	K	constitution
dConst	DK	direct constitution
inheres	qt	inherence
participates	PC	participation
partOf	P	part
pPartOf	PP	proper part
pre	PRE	presence in time
Accompl	ACC	accomplishment
Agent	APO or ASO	agent
Feature	F	feature
M	M	amount of matter
NonAgentiveSocialObject	NASO	non-agentive social object
Perdurant	PD	perdurant
PhysicalEndurant	PED	physical endurant
PhysObject	POB	physical object
Process	PRO	process
Quality	Q	quality
State	ST	state
TimeInterval	T	time interval