Resources in Manufacturing

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Abstract. Standards and ontologies for manufacturing differently understand resources. Because of this heterogeneity, misunderstandings arise concerning the basic features that characterise them. The purpose of the paper is to shed some light on the ontology of resources to strive the development of computational models for manufacturing. In particular, we propose various approaches for the representation of resources and address their advantages and disadvantages. We also present some preliminary considerations for the modelling of capabilities and capacities, as well as information, time, and money.

Keywords. Manufacturing resource, planning, systems design, PSL.

1. Introduction

The concept of resource is fundamental in various domains. Being a general term, it has been used in a variety of communities without becoming the subject of specific definitions, thus relying on the implicitly shared viewpoint among the community's members. This lack of characterisation and the possible mismatches in the understanding of the term jeopardise the efforts to share data models as well as to integrate information systems and services. According to the Oxford Dictionary of English (ODE), for instance, a resource is: "[a] stock or supply of money, materials, staff, and other assets that can be drawn on by a person or organi[s]ation in order to function effectively [...]."

In this view a resource is like an asset, i.e., an item that has value for and is owned by an agent. A resource does not need to be related to an action or plan; what is required is that it has a value for some agent to function as needed. E.g., an adjustable wrench is of value to a mechanic even though s/he does not foreseen any use for it today.

Once we move from broad dictionary definitions to application contexts such as manufacturing, the intended semantics of resource-related notions is narrower in such a way to match engineering views. Despite this, only little agreement is found across experts and stakeholders in the way in which *manufacturing resources* are conceived [22]. Consider, for instance, the following definitions of manufacturing resource: "Any

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device, tool and means, except raw material and final product components, at the disposal of the enterprise to produce goods and services" (ISO 15531); "A resource is an entity that provides some or all of the capabilities required by the execution of the enterprise activities and/or business processes. The types of resources involved in manufacturing operational management are: personnel, material, equipment (role based and physical asset) and process segments" (IEC 62264).

First, materials count as resources only in the second case. Second, IEC 62264 states that resources are needed to execute activities, while ISO 15531 is not explicit about this. An information system based on ISO 15531 could not therefore easily interoperate with a system based on IEC 62264 because of the mismatches in the employed models.

The purpose of the paper is to shed some light on the modelling of manufacturing resources to foster the development of domain-specific computational ontologies. In particular, we present across Section 2 three approaches for resource modelling by addressing their pros and cons; some general remarks on the approaches are discussed in Section 3. Section 4 presents an example for resource representation in the context of manufacturing system design, whereas Section 5 presents some considerations to model capabilities and capacities, as well as time, information, and money as resources. Finally, section 6 concludes the paper.

2. Manufacturing Resources

We discuss in this section three main approaches for the conceptualisation and representation of manufacturing resources. The purpose is to clearly distinguish and identify different ways in which resources are understood. Also, we introduce some first-order formulas to stress the differences between the approaches and to highlight how these affect the development of computational ontologies. A complete axiomatisation of each view is beyond the purposes of this work.

As seen in the introduction, the terminology is unfortunate since experts and stakeholders (as well as standards) rely on different and not well aligned vocabularies. For the sake of clarity, we will adopt the Process Specification Language (PSL) terminology [15] (ISO 18629), in particular for the distinction between *Activity* and *Activity Occurrence*. The latter are *processes* occurring in time, whereas the former are the conditions that activity occurrences satisfy. We therefore treat activities as *plans*, i.e., descriptions of (possible) activity occurrences. Admittedly, the choice of interpreting PSL activities as plans is debatable, since they may be also understood as activity *types*. The distinction between plans and activity types is however subtle and not relevant for what is presented in this paper; in addition, the correspondence between activities and plans has already been documented [15]. We will therefore interchangeably use the terms plan and activity; process and activity occurrence.

2.1. Manufacturing Resources and Activity Occurrences

Resources are often conceived in manufacturing as entities that participate in manufacturing processes [1,6]. This can be formally captured as in (Def1), where *PC* is the standard relation of *participation* holding between endurants and perdurants [7,15], whereas $MfgActOcc$ stands for manufacturing activity occurrence as defined in (Def2). Also,

$PRE(x,t)$ – 'x is present at timet t' – models the time at which an entity exists [7]; $\preceq$ and $\prec$ are the usual order relations on time; $outcomeOf$ is used to model the result of an activity occurrence, e.g., the product it fabricates.

Def1 $MfgResource(r) \triangleq \exists ot(MfgActOcc(o) \wedge PC(r,o,t))$
(r is a manufacturing resource iff it is the participant of a manufacturing activity occurrence)

Def2 $MfgActOcc(o) \triangleq ActOcc(o) \wedge \exists xt(Product(x) \wedge outcomeOf(x,o) \wedge PRE(x,t) \wedge \preceq (endOf(o),t) \wedge \forall t'(\prec (t', endOf(o)) \rightarrow \neg PRE(x,t')))$
(o is a manufacturing activity occurrence iff o is an activity occurrence that ends with the existence of a new product)

Definition (Def1) is really general. According to it, an entity is a resource even before the plan requiring its use is provided. Moreover, the product which is the outcome of a manufacturing activity occurrence might be itself a resource for that very occurrence. At the same time, this definition violates some basic intuitions. Take, e.g., two entities of the same type in the same manufacturing site; if one will participate in a manufacturing activity occurrence tomorrow and the other is never used, the first is a resource and the other one is not even though we do not know how to distinguish them today.

The generality of this claim is sometimes restricted to capture only certain processes' participants. For example, manufacturing resources are sometimes understood as persons or things that *add value* to a product in its production or delivery (see [21] for a similar approach). Although it remains unclear what "adding value" means, it suggests that resources contribute to the completion of the given manufacturing activity occurrence.

A further variation is adopted in works based on PSL [15], according to which manufacturing resources are *required* for certain activities to occur. The idea is that activities cannot occur without the specified resources. In the theory *PSL resources*[2] this is captured by axiom (Ax1) (rewritten in our notation), where occ_of – taken from *PSL Core*, see (Ax2) – holds between an activity occurrence and the activity it realises [15].

Ax1 $requires(a,r) \wedge occ\_of(o,a) \rightarrow \exists t(PC(r,o,t))$
(if activity a requires r, then for all occurrences o of a, r participates in o)

Ax2 $occ\_of(o,a) \rightarrow ActOcc(o) \wedge Activity(a)$
(occ_of holds between activity occurrences and activities)

According to this approach, the same individual resource is meant to participate in *all* occurrences satisfying the same activity. This has undesired consequences. For instance, the theory cannot deal with cases in which the pre-selected resource is not available, e.g., because it is under maintenance.

To conclude, this first approach results rather limited. It heavily relies on the relation between specific resources and activity occurrences. Since in manufacturing contexts experts often talk of resources in planning or scheduling scenarios where there are no individual manufacturing activity occurrences to which resources can be bound, it is clear that we need to extend this view.

[2]The reader can refer to the COLORE repository for a complete overview on PSL axioms; `https://github.com/gruninger/colore/tree/master/ontologies`. Last accessed in May 2019.

2.2. *Manufacturing Resources and Activities*

In this second perspective resources are conceptualised in tight connection to manufacturing activities (aka *plans*), i.e., specifications about the activity occurrences to be realised in manufacturing contexts (see, e.g., [12,22,23]). The rationale for this view is to be more general with respect to the aforementioned approach; hence, to weaken the direct link between resources and activity occurrences, it allows to refer to resources even in the absence of individual occurrences where they are meant to participate.

In manufacturing one can distinguish process plans and production plans. A *process plan* defines the sequence of manufacturing activity occurrences to convert a workpiece from an initial to a final form, where the plan incorporates the description of each occurrence, its parameters, and possibly even equipment and/or machine tool selection [19]. On the other hand, based on product demand/orders, a *production plan* determines which production resources are to be assigned to each occurrence on each workpiece, when each occurrence is to take place, while resolving contention for the resources [11]. A production plan incorporates therefore one or more process plans and resolves possible ambiguities in the process plan. Both process and production planning can be hierarchically addressed. For the sake of simplicity, the notion of manufacturing activity we assume includes both process plan and production plan.

The link between manufacturing resources and activities can be captured as in the following formulas where *sat* is a primitive relation holding between physical or temporal entities and the descriptions they *satisfy* (realise), see (Ax3). The *sat* relation can be therefore understood as a generalisation of occ_of in PSL (Ax2) that is useful to bind objects to the descriptions they satisfy. For the sake of this work, we take $Description$ as a primitive predicate standing for the repeatable 'content' of engineering specifications [18]. $Description$ is therefore the class of information objects and, as such, it is disjoint with *ActOcc* and physical objects. Also, we assume that if descriptions have parts, these are descriptions, too. Axiom (Ax4) introduces the relation *meantToProduce* which is used in (Def3) to define manufacturing activity. Looking at (Ax4), *PP* stands for *proper parthood* in classical extensional mereology [9] (for simplicity, *PP* is not temporalised), whereas *ProductDescr* is the description of the product that occurrences of the activity at stake are meant to physically realize (cf. relation $outcomeOf$ in Def2).

Ax3 $sat(x,y,t) \rightarrow PRE(x,t) \wedge Description(y)$

(if x satisfies y at t then x exists at t and y is a description)

Ax4 $meantToProduce(a,x) \rightarrow Activity(a) \wedge ProductDescr(x) \wedge PP(x,a)$

(a is an activity that includes as part the product description x)

Def3 $MfgActivity(a) \triangleq \exists x(meantToProduce(a,x) \wedge \forall o(occ\_of(o,a) \rightarrow (\exists y(Product(y) \wedge sat(y,x,endOf(o)) \wedge outcomeOf(y,o)))))$

(a is a manufacturing activity iff it is an activity such that all its occurrences have as outcome a product whose description is part of the activity)

With these basic notions, manufacturing resource can be defined as in (Def4)–(Def5), where *resourceFor* captures the relational link between resources and activities. Accordingly, a manufacturing resource is an entity that satisfies the manufacturing resource description (primitive predicate) included in the activity at stake.

Def4 $resourceFor(r,a,t) \triangleq MfgActivity(a) \wedge \exists x(MfgResourceDescr(x) \wedge PP(x,a) \wedge sat(r,x,t))$
(*r* is a resource for the manufacturing activity *a* iff *r* satisfies the resource description *x* included in *a*)

Def5 $MfgResource(r) \triangleq \exists at(resourceFor(r,a,t))$
(*r* is a manufacturing resource iff it is a resource for at least one manufacturing activity)

To conclude, this approach allows to deal with the representation of manufacturing resources without *necessarily* committing to the manufacturing activity occurrences where they possibly participate. The approach is therefore more flexible than what discussed in the previous section, since – as said – one may wish to talk about resources without binding them directly to occurrences. Note however that the introduced definitions, beside being developed to a limited extent, aims to model only a weak notion of resource since, for instance, there is no requirement about relevant states of the resource like availability or ownership. These constraints might be added as additional conditions depending on the scenario and the specific application one is working with.

2.3. Manufacturing Resources and Goals

We explore in this section a third approach to represent manufacturing resources based on goal modelling [22]. The idea is that manufacturing resources are entities employed in manufacturing environments to bring about agents' goals, e.g., the goal of making a product with the desired characteristics. The advantage of this view over the previous ones is the possibility of modelling resources independently from the plans to which they are possibly related. For instance, one may conceive a driller as a manufacturing resource only because the driller is functional to achieve certain goals, rather than because there is a plan for a drilling process covering the description of the driller. From this point of view, the approach presented in this section weakens what discussed in Section 2.2 in such a way to allow for resources modelling in the absence of manufacturing plans.[3] Before presenting some formal aspects, let us look at the notion of goal.

Following the Belief-Desire-Intention approach (BDI) [10], one can understands goals in terms of agents' mental qualities referring to *desired states of the world*. This view needs however to make sense of *goal sharing* (common in manufacturing contexts), e.g., when one wishes to model multiple agents having the same goal towards the production of a certain product. An alternative way to represent goals without relying on individuals' mental states consists in objectifying and treating them as *descriptions* of desired world states. For instance, the goal of agent *A* (e.g., a manufacturing organisation) to *have a product with characteristics B and C* is satisfied by a world state where a product with characteristics B and C exists.

Similarly to the approach in Section 2.2 to represent descriptions, axiom (Ax5) gives a minimal constraint on the relation *goalForAgent*. Looking at the axiom, *State* is a primitive predicate standing for a perdurant whose (temporal) parts are all of the same type [17]. The *goalForAgent* relation is used in (Def6) to define manufacturing goal. (Note that, generally speaking, relations *goalForAgent* and *desires* should have also a temporal parameter as an agent may change desires over time.)

[3] Reference to goals is often implicitly done in manufacturing through either processes or plans.

Ax5 $goalForAgent(x,y) \rightarrow Description(x) \wedge Agent(y) \wedge \forall st(sat(s,x,t) \rightarrow (State(s) \wedge desires(y,s)))$

(*goalForAgent* holds between a description x of a state and an agent y, such that y desires any state that satisfies x)

Def6 $MfgGoal(x) \triangleq \exists y(goalForAgent(x,y) \wedge \forall st(sat(s,x,t) \rightarrow \exists v(Product(v) \wedge PC(v,s,t))))$

(x is a manufacturing goal iff there is an agent y such that for each state s realising x there is a product v which participates in s)

By looking at (Ax5) and (Def6), a manufacturing goal is satisfied by a state of the world in which there is a product that satisfies the agent's goal. Also, the formulas bind goals neither to manufacturing activities nor to their occurrences, i.e., they do not specify *how* the state and the product are obtained. As said, this third approach captures the notion of resource by directly linking it to goals rather than plans or processes.

Manufacturing resource can be now defined by means of a relation $resourceFor^*$, which binds a resource to an agent's goal(s) (Def7) independently of the way the goal is achieved. Both formulas can be strengthen to capture different kinds of resources, e.g., *mechanisms* like machines or tools that 'actively' contribute to achieve the goal, or *inputs* like amounts of matter that undergo manufacturing activity occurrences [22].

Def7 $MfgResource(r) \triangleq \exists x(resourceFor^*(r,x) \wedge MfgGoal(x))$

(r is a manufacturing resource iff it is a resource for a manufacturing goal)

In order to model the link between goals and the manufacturing activity occurrences bringing them about, manufacturing activity can be defined as in (Def8). Accordingly, a manufacturing activity has a goal so that each occurrence satisfying the activity has outcome a world state satisfying the goal and therefore the product participating in the state.[4]

Def8 $MfgActivity(a) \triangleq Activity(a) \wedge \exists y(MfgGoal(y) \wedge PP(y,a) \wedge \forall o(occ\_of(o,a) \rightarrow \exists s(sat(s,y,endOf(o)) \wedge outcomeOf(s,o))))$

(a manufacturing activity is an activity that includes a manufacturing goal which is satisfied by the state achieved at the end of any activity occurrence)

3. Remarks

The three approaches presented in the previous section are distinct views on manufacturing resources. As seen, the first approach (Section 2.1) is well suited to model resources in tight connection to manufacturing activity occurrences. On the other hand, it is less exploitable for application cases where resources are to be managed independently from the manufacturing processes where they only possibly participate. The second view (Section 2.2) deals with this issue by binding resources to activities (plans) rather than occurrences. A manufacturing resource is therefore an entity that is functional for a manufacturing activity. Finally, the third approach (Section 2.3) is more general and flexible

[4] For simplicity, we use the relation $outcomeOf$ for representing both states and products resulting from activity occurrences.

than the previous ones, since it models resources independently from both activities and occurrences but in connection to agents' goals.

It should be clear that the choice of adopting one approach or the other depends on experts' requirements and the way in which they wish to make sense of resources. It can be argued indeed that each approach fits a subset of factory lifecycle phases: Manufacturing execution when the system configuration is given (Sect.2.1); Detailed system design or production planning when the set of products is known and process planning has been carried out (Sect.2.2); Early system design when limited details about product and activities are available (Sect.2.3).

Considering that planning and scheduling tasks play a fundamental role, the second approach is definitely central to manufacturing modelling. The third approach could be easily integrated with the second one by representing goals in tandem with plans. Inevitably, this would increase the (conceptual) expressivity of the ontology, since it would bring into the overall framework both goal descriptions and plans. From an application perspective this complexity might be undesired. Also, the approach in Section 2.2 *does* refer to the item that an agent wishes to produce even though this is not stated in terms of goals. In addition, axioms can be added to explicitly model activity occurrences in tandem with activities and resources.

Finally, it must be noted that – independently from the approach one relies on – manufacturing resources are conceptualised as *roles*. Accordingly, an entity is not a manufacturing resource *per se* but it *counts as* (*has the role of*) manufacturing resource only when certain conditions are met. E.g., when it participates in a manufacturing process or is bounded to either an activity or goal.

4. Representing Manufacturing Resources: Design of Manufacturing Systems

This section presents an industrial use case where the modelling of manufacturing resources plays a key role. The use case is focused on the design of manufacturing systems where an ontology-based approach can support the integrated factory design by providing a shared common model that can consistently evolve during the design phase. In particular, the use case deals with the design of an assembly line as described in [2,3,5] (powertrain valve assembly on a cylinder head). The following input data are given in the current design phase: Process plan of the product to be assembled; set of sequential operations decomposing the process plan; input component or material for each operation; production resources needed to execute each operation.

Several design decisions need to be taken at this stage, e.g., the assignment of operations to workstations in the line (i.e., line balancing), selection of production resources for each workstation (i.e., line configuration), optimisation of the capacity of inter-operational buffers (i.e., buffer allocation problem).

Table 1 reports some relevant data defining the use case, namely, the list of operations (ID and description); component or material inputs for each operation (WIP stands for 'work in progress', i.e., resulting from the previous operation); resources needed to execute each operation. For the sake of the example, we focus herein only on the resources needed in automatic stations. Each resource can be further characterised in terms of failure modes, investment and operating cost, size, etc. The processing time may depend on the resources employed to execute the operation. Moreover, if more than one operation is assigned to the same workstation, the latter must include the production resources needed for all operations to be performed.

Table 1. Use case data

Operation ID	**Operation Description**	**Input component or material**	**Resources in Automatic Station**
op10	Load and identify cylinder head	cylinder head	palletizing robot
op20	Apply sealant and lubricant	WIP, sealant and lubricant	robot, sealant dispensing tool
op30	Install intake and exhaust valves	WIP, intake and exhaust valves	robot, handling gripper
op40	Valve blow-by leak test	WIP	robot, leak test tool
op50	Rollover	WIP	rollover equipment
op60	Assemble valve stem seal	WIP, valve stem seals	robot, handling gripper
op70	Press valve stem seals	WIP	robot, pressing tool
op80	Assemble valve springs	WIP, valve springs	robot, handling gripper
op90	Assemble valve spring retainer	WIP, valve spring retainer	robot, handling gripper
op100	In process verification	WIP	robot, verification tool
op110	Unload cylinder head assembly	WIP	palletizing robot

Even though the process plan is linear, various feasible system configurations can be designed based on the requirements and the selectable resources. Line balancing and line configuration will be carried out by considering objective function and constraints related to investment cost, operating cost, throughput, etc. [5]

We now apply the approach of Section 2.2 to the data in the table. Input data can be provided to a methodology supporting the design of the assembly line and its results can be used to instantiate the ontology specifying the chosen system configuration.

Since the formalizations in Section 2 did not aim at completeness with respect to manufacturing modelling needs, extensions are necessary. We adopt definition (Def9) for complex (manufacturing) activities, that is, activities formed by at least two (different) activities. Conversely, (Def10) introduces manufacturing operations as activities that are not complex. Admittedly, these two definitions only weakly characterise these notions but suffice here to present the general view.

Second, by looking at Table 1, each entry in the Operation ID column refers to either specific operations or to specific complex manufacturing activities. In each case, they are part of the complex manufacturing activity standing for the entire planned activity; let us call $cxact\_1$ this latter entity (the activity including all other activities in the table). Entries in the Operation column refer to classes of manufacturing activities, e.g., *Load* and $IdentifyingCylinderHead$ refer to the activities of loading raw parts and of recognising the heads of cylinders for assembly purposes (axioms like (Ax6) can be used to exhaustively cover the table). Entries in the final two columns model manufacturing resource descriptions. In particular, the *Input component or material* refers to resources that are inputs for manufacturing processes and are therefore manipulated during the processes, whereas *Resources in automatic station* describes resources that either execute a process (i.e., a robot) or support it (e.g., handling gripper). Domain experts in these cases require the flexibility of describing either classes of manufacturing resource or individual resources, e.g., descriptions satisfied only by robots owned or sold by a certain enterprise. For the sake of the example, (Ax7) introduces two (disjoint) resource description classes.

Def9 $MfgComplexActivity(x) \triangleq MfgActivity(x) \wedge \exists yz(MfgActivity(y) \wedge MfgActivity(z) \wedge PP(y,x) \wedge PP(z,x) \wedge y \neq z)$

Def10 $MfgOperation(x) \triangleq MfgActivity(y) \wedge \neg MfgComplexActivity(x)$

Ax6 $Load(x) \vee IdentifyCylinderHead(x) \rightarrow MfgActivity(x)$

Ax7 $PalletizingRobotDescr(x) \vee CylinderHeadDescr(x) \rightarrow MfgResourceDescr(x)$

The first row of the table can be represented as follows.[5] Formula (f1) introduces the complex activity $op10$ formed by an instance of *Load* and an instance of *IdentifyCylinderHead* such that whenever $op10$ occurs, the load occurrence precedes the identify cylinder head occurrence.[6] Formula (f2) introduces the complex activity $cxact\_1$ comprising $op10$ and all activities listed in the table above (ideally this formula should include also their order of execution). Formula (f3) makes explicit the resource descriptions related to $op10$. In particular, a specific cylinder head description is in play, i.e., $ds1$; this could be further characterised to model, e.g., the dimension, weight, capability, technology provider, etc. that a physical resource has to satisfy. Differently, the formula does not cover an individual description for the palletizing robot; it only says that $op10$ includes the description of a (generic) palletizing robot. In this way, experts can avoid to commit to a specific description, which they may introduce along the modelling process when their requirements are more explicitly defined.

f1 $Load(load10) \wedge IdentifyCylinderHead(identify10) \wedge PP(load10, op10) \wedge PP(identify10, op10) \wedge load10 \prec identify10 \wedge MfgComplexActivity(op10)$

f2 $MfgComplexActivity(cxact\_1) \wedge PP(op10, cxact\_1)$

f3 $CylinderHeadDescr(ds1) \wedge PP(ds1, op10) \wedge \exists x(PalletizingRobotDescr(x) \wedge PP(x, op10))$

The distinction between input resources and supporting or mechanism resources, present in Table 1, has not been formalized here. On this topic see, e.g., [16]. In general, the formal approach presented in Section 2.2 provides only high-level modeling elements that can be extended and adapted to match specific views in the manufacturing domain. Also, one can model the activity occurrence(s) satisfying the operations as introduced above along with the outcome product and the used physical resources. Further axioms are needed to qualify the participation of resources (e.g., with respect to time constraints), or to model *alternatives* in resource selection (e.g., the possibility of using automatic *or* manual stations).

5. On Capabilities, Capacities, Information, Time and Money

We discuss in this section preliminary considerations concerning the notions of capability and capacity (Section 5.1) as well as extensions of the notion of manufacturing resource to cover information, time, and money (Section 5.2).

[5] We label formulas relative to the examples with f.

[6] With a slight abuse on notation, we use $\prec$ to temporally order (the occurrences of) activities.

5.1. Capabilities and Capacities

Resources are commonly characterised in terms of both *capabilities* and *capacities* in manufacturing. According to MANDATE, for example, "a resource capability defines a group of characteristics specifying manufacturing resources under *functional aspects*" (MANDATE-31, p. 12; emphasis is ours). In addition, the standard relies on capabilities to constrain the participation of resources to manufacturing processes by adding that a capability is the "quality of being able to perform a given activity." An example is the capability of a cutting tool *to remove (a certain type of) material within certain dimensional tolerances*. Hence, the tool can be used in a cutting activity occurrence aimed at realising a feature (e.g., hole, slot) only because of its capability. On the other hand, capacity is a "measure of the quantity of product (or component) a resource can process per unit of time" (p.24). Although it is hard to find explicit definitions of these notions, the MANDATE view seems shared by most manufacturing experts and stakeholders.

Focusing on capabilities, from the definition above it is clear that MANDATE understands them as functionalities. The latter are notoriously differently understood in engineering [13] and, as a consequence, differently represented in ontologies (see, e.g., [14]). A comparative analysis of these approaches with respect to manufacturing, similar to what done throughout Section 2, is left to future work. As said, we sketch in the following only some preliminary considerations.

Recent works based on the Basic Formal Ontology (BFO) for manufacturing propose to conceive and represent capabilities as *dispositions* [20]. Leaving aside the philosophical debate on these entities, they are commonly understood in applied ontology – including BFO – as characteristics of objects which are *manifested* only if specific circumstances occur (see, e.g., [4]). For instance, the capability of a magnet to attract metal qualifies the magnet whenever the latter exists. However, this disposition manifests only when the magnet is close to a piece of metal and, therefore, may never manifest. A similar approach is discussed in [8]. Differently from [4,20], the authors do not model the manifestation of dispositions and treat them as plain (artefacts') qualities. The two approaches rely therefore on different ontological views. Approaches like [4,20] inevitably lead to conceptually and formally complex ontologies, since they must take into account the conditions triggering the manifestation of dispositions. The approach in [8] avoids this complexity while being able to represent capabilities. Recalling the way in which MANDATE binds resources to processes via capabilities, the work in [8] could be used to specify constraints like: *Resource r can participate in activity occurrence o only if it has capability c*.[7]

Turning now to capacities, note the similarity with capabilities: the latter model *what* a resource is able to do (e.g., to cut or add material), the former *how many* things it does (e.g., a polished threaded hole each 5 minutes). Capacities could be therefore understood as (sub-types of) capabilities making explicit the maximum number of products a resource is able to manipulate for a time unit.

5.2. Information, Money and Time as Resources

The manufacturing literature on resources concentrates on material and agentive resources since these are at the core of manufacturing activities. Section 2 has adopted

[7]Considering the differences discussed in Section 2, these constraints need to be specified in relation to the way in which resources are conceived, e.g., with respect to activities or activity occurrences.

this view. However, material and agentive entities do not exhaust the type of resources experts talk about in this domain. Even before the Industry 4.0 emphasis on data and information, it has been known that these have a central role in modern production systems. Accordingly, the formalisation discussed in the previous sections deals with data and information along with material and agentive resources, that is, they are not treated as a separate type of resource that needs a distinct modelling approach.

The situation is different when we move to talk about money and time as resources. Money is definitely a resource in both colloquial and technical discussions but money is not discussed in modelling manufacturing scenarios. We believe that the explanation is quite simple. Money participates in property exchanges (acquiring and selling) and not in production activities. When one talks of money as a resource, s/he implicitly refers to a (perhaps just possible) business process where money participates as one of the exchanged entities. This means that money is not a resource in a mere manufacturing setting. It is a resource when we augment a manufacturing process with processes about business transactions, e.g., for acquiring a device or ensuring the availability of an agent which then participates to the manufacturing activity.

Finally, many discussions about time look at it as a resource: "It takes 48 hrs to produce this item but we only have 36 available", "we have enough time to operate that machine." We thus posit the question: is time a resource? Since a resource is a role, this means to answer this other question: what is the role of time in manufacturing processes? Clearly, time does not participate to a process, nor it acquires a different status when we look at time from the point of view of an activity. The underlying idea is that when we talk of time as resource, we actually mean either the availability of the production resource for a manufacturing process, availability that comes to an end at the delivery time since this constraint is part of the plan description, or the availability of a device which is a resource for the plan in the sense discussed in Section 2. In either case, it turns out that time is not a resource in the manufacturing sense; therefore, talking of time as a resource should be treated as a way of speaking without any explicit ontological commitment.

6. Conclusions

The research work presented in this paper strove from the need of making explicit some of the foundational assumptions behind resource modelling in manufacturing. In particular, the work presented across the first sections presents existing approaches by addressing their pros and cons. As said, the three approaches are well motivated from both an ontological and manufacturing stance; the choice of relying on one or the other depends therefore on the modelling requirements that the ontology at stake should satisfy, and on the level of abstraction one wishes to achieve. The approach discussed in Section 2.2 allows to gain a good compromise between expressivity and modelling flexibility for the fact that resources are not directly bound to activity occurrences but on their plans.

Future work is required to strengthen both the formal and conceptual treatment of resources. In particular, Section 5 presented some preliminary ideas which require further analysis to be modelled in a robust way. A computational formalisation is also needed for reasoning over manufacturing knowledge and organising data for application purposes.

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