OMNIMETAL
Vinnova project 2018-04321

Digital twin concept data model of metal

Summary

This report presents the concept data model for the digital twin of metal, from specification of metal product to definition of scrap yard, and from scrap yard to final metal product. The report leads the reader from the basic needs of data-based foundry production management system through logic steps to the model where all key concepts for the data model is presented.

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1. Introduction

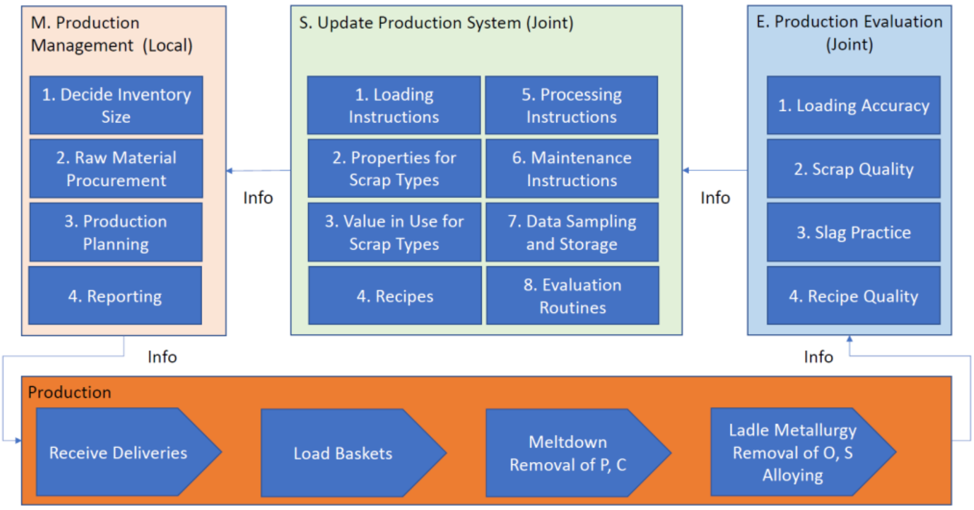

Figure 1. A data-based management model of a general foundry. (Rutger Gyllenram, Kobolde AB)

Figure 1 depicts an information flow of the management of a foundry. The *info* arrow going from *Production Management* to *Production* represents some control signal, such as an operators' increase of effect to a melter or production management's signal to start a quality improvement campaign. The *info* arrow coming from *Production* to *Product Evaluation* represents providing performance data to evaluate, such as temperature of the melt or the number and type of quality errors. The *info* arrow going from *Product Evaluation* to *Update Product System* represents to provide the control and management functions with accurate and transparently evaluated performance data. The info arrow from to *Update Product System* to Production management represents that the data-based production management utilizes the information provided by the data-based control and management functions.

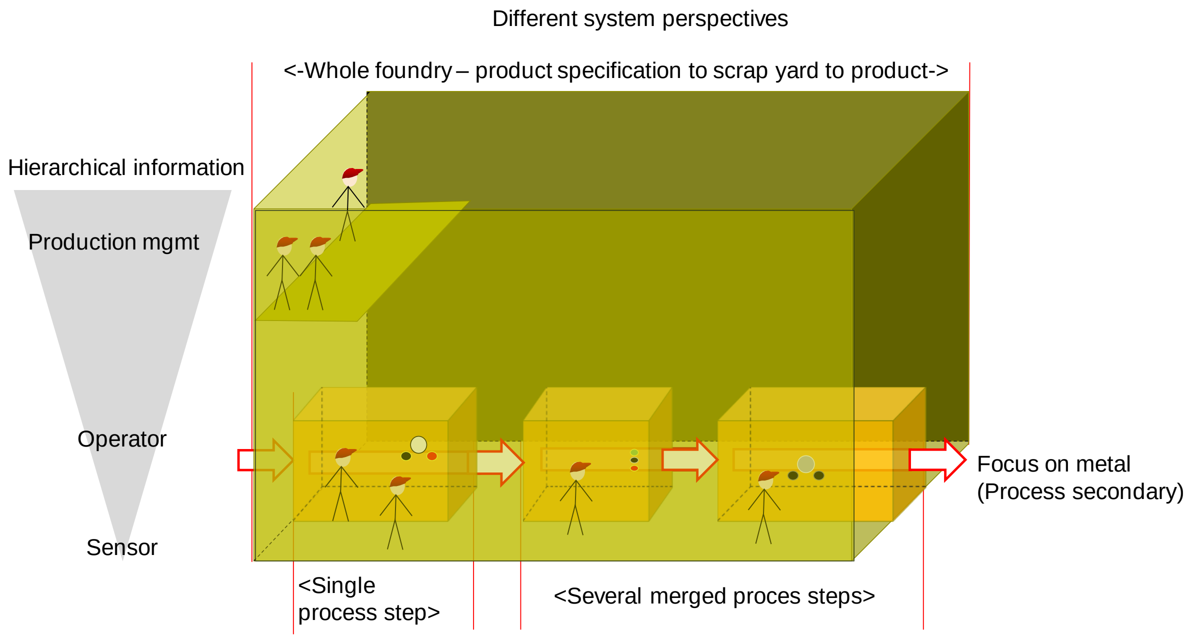

Figure 2. Schematic picture showing the flexibility of system perspectives, of system and management aligned flexibility of hierarchical information aggregation, and the focus on metal.

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Figure 2 is a schematic picture showing the dimensions of flexibility required of the design of the digital twin of the metal of the foundry to meet the general needs of foundry production management depicted in Figure 1. The data and information of the digital twin need to allow for information transparency and aggregation between individual sensor data and individual process steps to strongly aggregated information useful for a site management, this matches the different system perspectives at which a foundry needs to be seen for the control from product specification to scrap yard and from scrap yard to final product. Figure 2 also stresses that the focus of the digital twin is at the metal, through its different compositions, transitions, phases, forms and processing through the foundry.

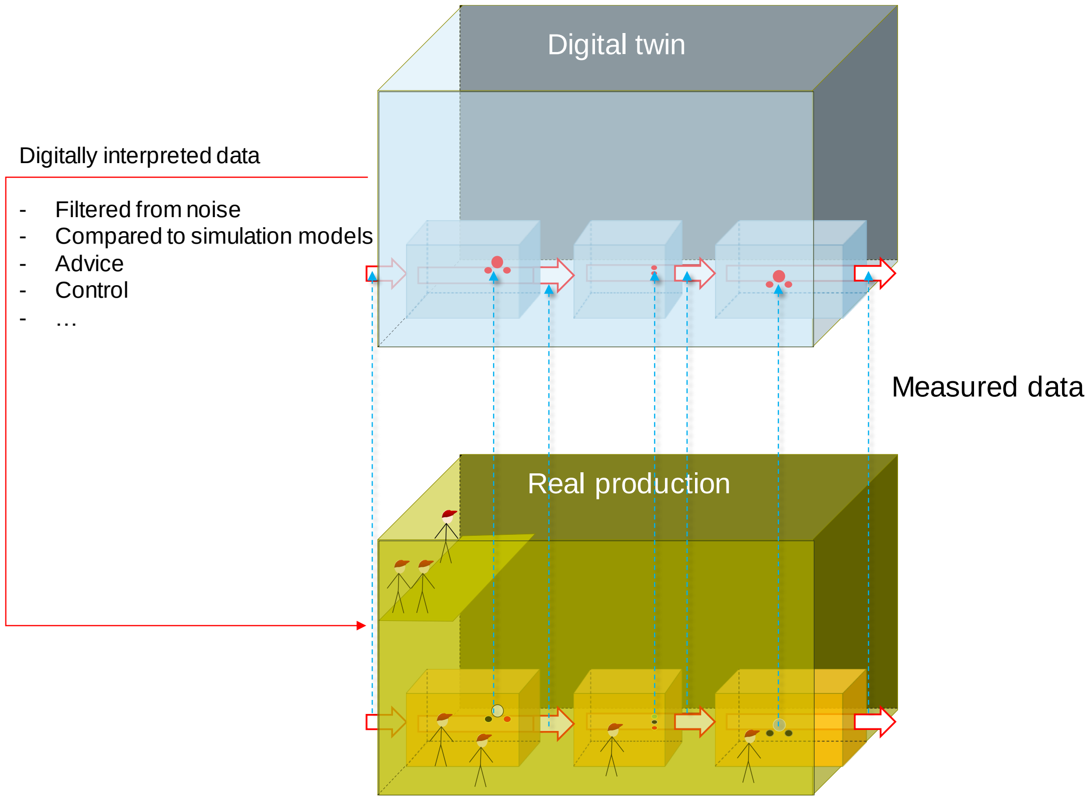


Figure 3. Schematic picture showing how the model of the digital twin of the metal matches the real production through acquiring representative data about the metal from the real production.

Figure 3 shows how the model of the digital twin provides a digital representation of the metal throughout a digital twin of the foundry process. The matching (or calibration or synchronization, depending application) between the digital twin and the real production is achieved by measurements that provide good representations of properties of the metal in the real production at known or defined positions and times.

2. Digital twin data model

2.1 High-level digital twin model

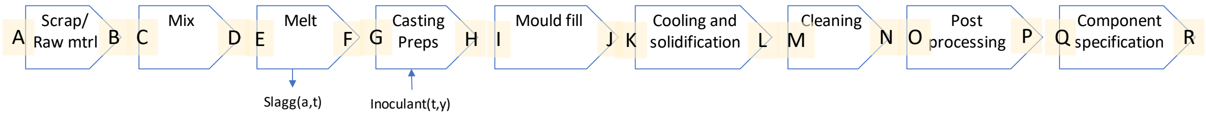


Figure 4. Representation of a high-level division of the cast metal digital twin through the stages of a foundry from scrap yard to meeting product specifications. Capital letters A-R represents significant metal properties in to and out from the foundry stages.

Figure 4 shows a somewhat arbitrary high-level division of the cast metal digital twin through the stages of a foundry from scrap yard to meeting product specifications. The meaning of each stage

- **Scrap/Raw mtrl**: The specification of the available metal at the scrap yard of a foundry. The specification may be based on for example an inventory or on the bill of laden provided by the supplier.
- **Mix**: The specification of the mix provided into a specific melt. It is based partly on the scrap available on the scrap yard, partly on the recipe for the melt.
- **Melt**: Specification of the metal in the melt, including the metal mix, any additional metal or alloys, the different slag removals during the melting, as well as the temperature, and any temporal, thermic or mass dynamics and volume distributions, hence a chemistry, mass, time and volume dependant specification.
- **Casting Preps**: Treatments before mould filling, including adding inoculants, decreasing temperature, etc.
- **Mould fill**: A specification of significant differences and distributions of melt temperature, pouring speed and shape of beam, as well as the liquid metal's behaviour inside the mould. This also includes aspects such as the metal's interaction with the mould coating, sand and other chemical or physical properties of the mould surface.
- **Cooling and solidification**: Temporal, chemical as well as phase- and space-distributed specifications of the cooling and solidification, with respect also to interactions with mould surface, heat gases etc.
- **Cleaning**: In a sand mould foundry this means the cast metal component during and after the removal of the remainders of the sand mould. In a high pressure die cast foundry this step does not exist.
- **Post processing**: The cast component during and after removal of excessive casting metal material of inlet and gating system, after correcting any casting errors, and after grinding, drilling and polishing the cast components with intention to meet Component specification.
- **Component specification**: The component specification, including acceptable degree of deviation from specification of metal alloy, material porosity and measurements of dimensions.

In Figure 4 capital letters A-R represents significant metal properties in to and out from the foundry stages. The purpose of each of the foundry process stages is to receive metal with some specified properties and to change the properties of the metal so that it can feed the next process stage. The following formulas are examples of high-level mathematical specifications of the relationships between input from one foundry process stage of Figure 1 into the next stage. To the left are the specifications of the inputs and outputs. To the right are parameters that either need to be measured, modelled or specified to specify a particular input or output metal specification.

Table A: High level mathematical expressions for metal input and output of foundry process stages.

Specifications of the inputs and outputs
A = scrap delivered from market
B = A(t, atmc)
C = B
D = Mix(C, recipee)
F = Melt(t, E(t), Slagg(a,t), u(t), X(t), T(t), Atm(t), F(t-1))
F = G
H = v(G(th), t, Inoculant(t,y), pb(t))
I = H
J = Z(v(th,t), Z(S), gv) K = J
L = K(t, Inoculant(th,t,u), U, S, crimp, tension)
M = L
N = Z(M,U,Y)
O = N
P = S(L,N)
Q = P
Rver = Ver(Q,R)

Table B: High level parameter Parameters of foundry metal to be measured, modelled or specified.

Parameters to be measured, modelled or specified	
t	time variable
a	Material analysis, absolute amount
y	Inoculant material
u	Rest material left in oven
T	Temperature
X	Measure of circulation in melt
th	Moment in time when casting starts
v	Pouring speed, i.e. mass of melt per second leaving the ladl
S	Design geometry
Z(S)	Cavity geometry
U	mould quality properties (porosity, consistency, coating, etc)
Y	Cleaning method and details of process
Rver	Resulting component according to some method to verify that it needs the specifications
atmc	Actual atmospheric chemistry
pb	The velocity and shape of the pouring beam
gv	The direction of the gravity vector
crimp	Material crimping
tension	Material internal tension build-up

The equalities and mathematical expression in Table A and the parameters specified in Table is highly simplified. This is mainly due to that the modelling is done from a top-down perspective, with the intention to gradually specify these parameters in a systematic way. Section 2.2 presents the standardised systematic way to related system level information into individual parameters.

2.2 Relating high system models to parameters and measured data

The International Organization for Standardization (ISO) has developed a guideline to respond to the general difficulty to systematically and transparently relate high-level systems quantifications into their basic parameters and data sources. The full name of this standard is ISO 14033:2019 – Environmental management – Quantitative environmental information – Guidelines and examples (from here referred to only as ISO 14033).

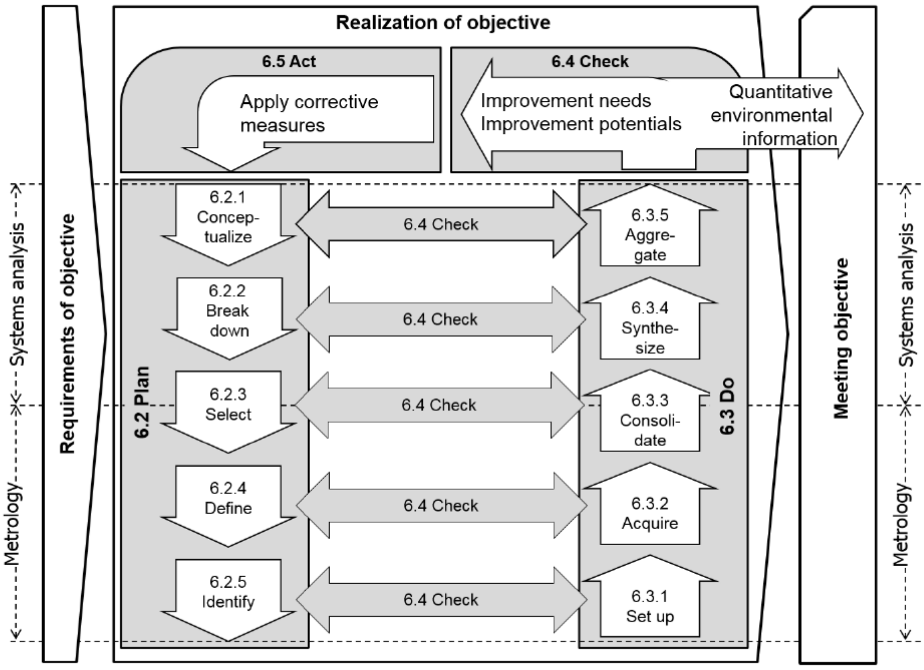


Figure 5. The graphical representation of the framework of ISO 14033 (copyright ISO 2019).

Figure 5 presents the graphical representation of the framework of ISO 14033. As can be seen to the very left and the very right of the figure, the model connects Metrology (the techniques and technologies of measuring) with Systems analyses (the techniques and methodologies of analysing systems). The core of the framework is within the grey boxes and arrows.

The left-side greyed box says **6.2 Plan**, and the arrows are going from *6.2.1 Conceptualize* down to *6.2.5 Identify*. The meaning of this is that when applying a top-down plan to specify the data needed to quantify and control a system at detailed level, one need to 1) acquire a full conceptual idea of which the total system is, and what type of information one need to know about it (think for example of each foundry process stage in section 2.1, and how we need to know the specification of the output from each process stage). 2) find an appropriate way to break down the whole system into more easily assessed subsystems (this can be done iteratively until the system is easily analysable). 3) decide exactly which parameters you want from each system level in order to calculate or otherwise derive the result defined at step 1. 4) Define which types of data sources you need to find or set up to get the data you need to quantify the parameters set in step 3. 5) Specify exactly where to get the data, such as from which position, which type of sensor, at which sampling frequency, etc.

The right-side grey box says **6.3 Do**. This means to do exactly what has been specified during plan, with regards to 1) setting up a measurement system (or however data has been planned to be acquired), 2) sample the data, 3) perform necessary statistics and other calculations to quantify the parameters, 4) quantify the subsystems, and 5) quantify the intended system.

It should be noted that ISO 14033 is structured as a Plan-Do-Check-Act continuous improvement loop, implying that it is intended that one can start simple and improve in all ways, to establish more and more subsystems and parameters as well as more and more precise definitions and implementations of measurements etc.

For more detailed information about ISO 14033 contact ISO at www.iso.org or your national standardization body.

2.3 Core digital twin concept model

2.3.1. General

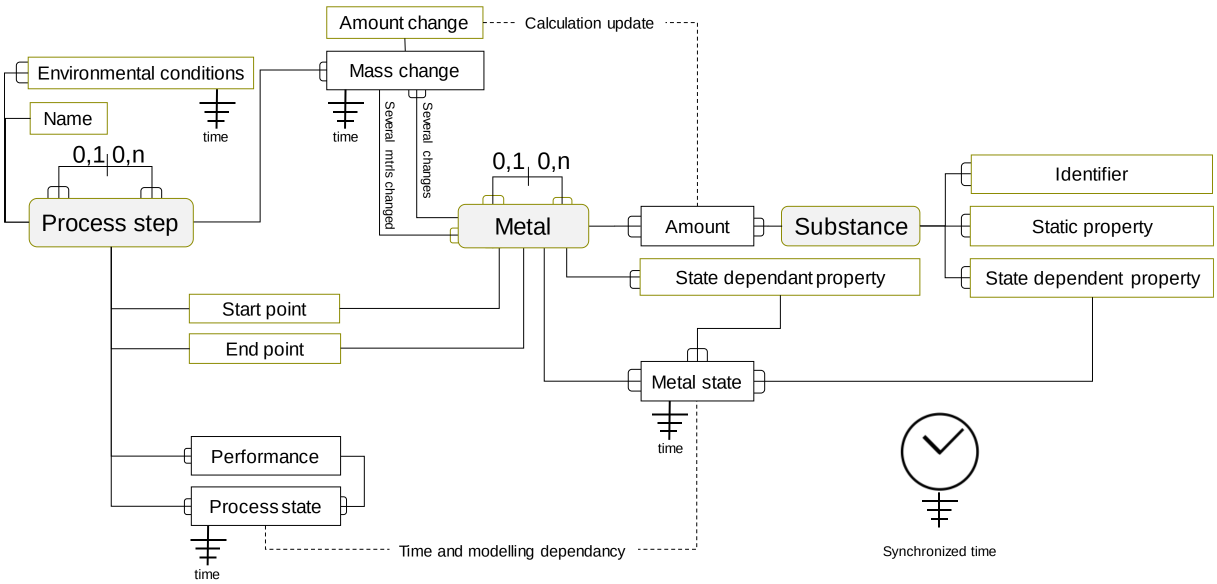
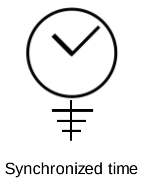


Figure 6. Core dynamic concept model intended to define the data model for the digital twin of metal.

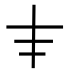
Figure 6 presents a core concept model intended as high-level model to guide implementation into a digital twin for metal in the metal process industry. The model should be understood as the logic connection between the high-level digital twin model presented in section 2.1 and as the lowest level data item acquired when using the systematic framework of ISO 14033 presented in section 2.2. By utilizing the structure of Figure 6 all data items necessary to describe the metal from scrap yard to final metal component may be described.

However, it shall be stressed that this is basically the concept model, and that the data an all calculation principles are still to be identified, developed and defined.

Time



Synchronized time: When time or sequence is of significance, it is important that all time keeping is synchronized, so that for example the timeline of the process is synchronized with the timeline of the metal.


time

time: The actual time being logged.

Foundry process stage

- *Process step*: The process step can either be the entire foundry, or one specific foundry process stage, or even a distinct and limited part of one process foundry stage.
- *Name*: A Process step needs to be identified by some name or other exclusive identifier.
- *Start point*: As given by capital letters in Figure 4 and Table 2 start points are given in terms of a metal specification.
- *End point*: As given by capital letters in Figure 4 and Table 2 end points are given in terms of a metal specification.
- *Performance*: A process has a specific performance, such as max electric power, max charge mass, max tipping degree, etc.
- *Process state*: Process state is the actual state of for example power, charge mass or tipping degree.
- *Environmental conditions*: A time dependant property, such as humidity, temperature, other chemical composition of atmosphere etc.

Cast metal

- Substance: a specific substance of which the cast metal is constituted. A cast metal consists of several substances.
  - *Identifier*: A substance may be known by many names.
  - *Static property*: A substance may have many different static properties, such as atomic weight, density, melting temperature, etc.
- Metal: A metal is constituted by substances. A metal may also been seen to be constituted by several metals (0,n)
  - *Amount*: Each substance is constituted by a specific amount.
  - *State dependent property*: A metal can have different state dependent properties, such as viscosity, velocity, and different micro-states depending on temperature, mix rate or alloy.
  - *State dependant property*: Emergent state dependant properties different from the state dependant properties of the substances that constitute the metal.
  - *Metal state*: At a specific point in time a metal has a specific state, such as a certain phase and velocity.
- Mass change: The total mass and mass constituency of a piece of metal may change due to additional charge, addition of alloys or inoculates, due chemical transitions, due to slag removal or pouring out from the ladle.
  - *Amount change*: The amount of shift of different constituting substances may be different.
  - *Several changes*: One specific piece of metal may be subject to several mass changes.
  - *Several mtrls changed*: Each change can subject several of the constituent metals.

Calculated or measured dependencies, i.e. other dimension than this conceptual model

- *Calculation update*: The actual change of substance is an update based on recipe, material analysis, or other data update.
- *Time and modelling dependency*: The data model of the Process step and the data model of the Metal are independent of each other. They need to be synchronized by e.g. synchronized

time or by physical model dependency. However, the division between the two is strictly intentional, to clearly and distinctly establish a digital twin of the metal.

2.3.2. Data model requirements: Scrap Raw material

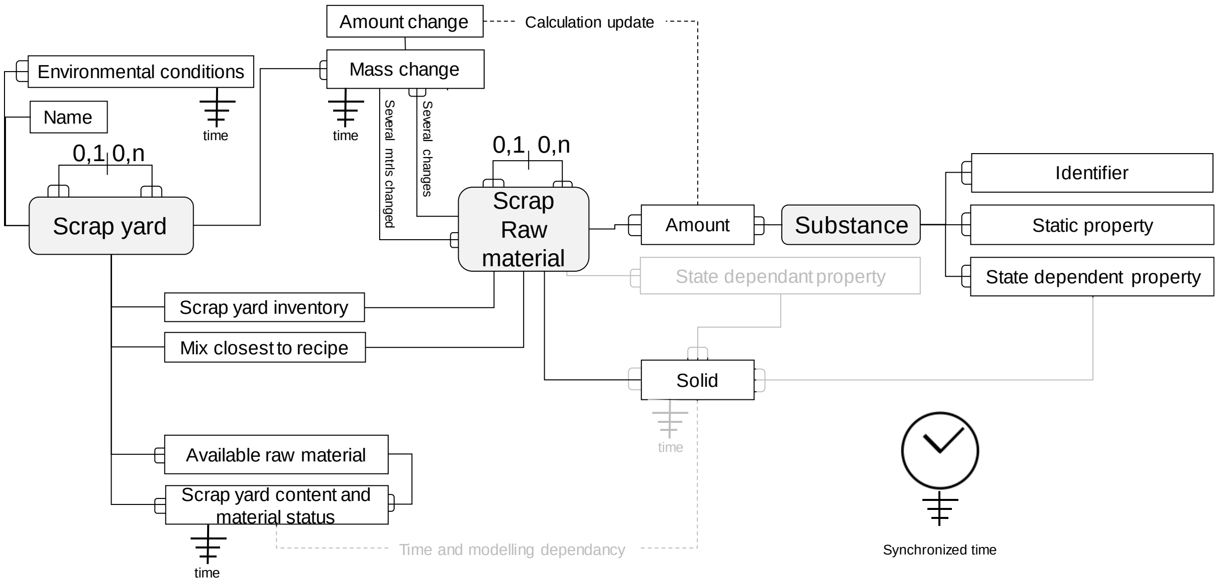


Figure 7. Concept model to dynamically describe the Scrap Raw material at the scrap yard

Scrap raw material – a selection of substances added to or removed from the scrap yard.
Scrap yard – a collection of different substances in a specific environmental condition.

2.3.3. Data model requirements: Mix

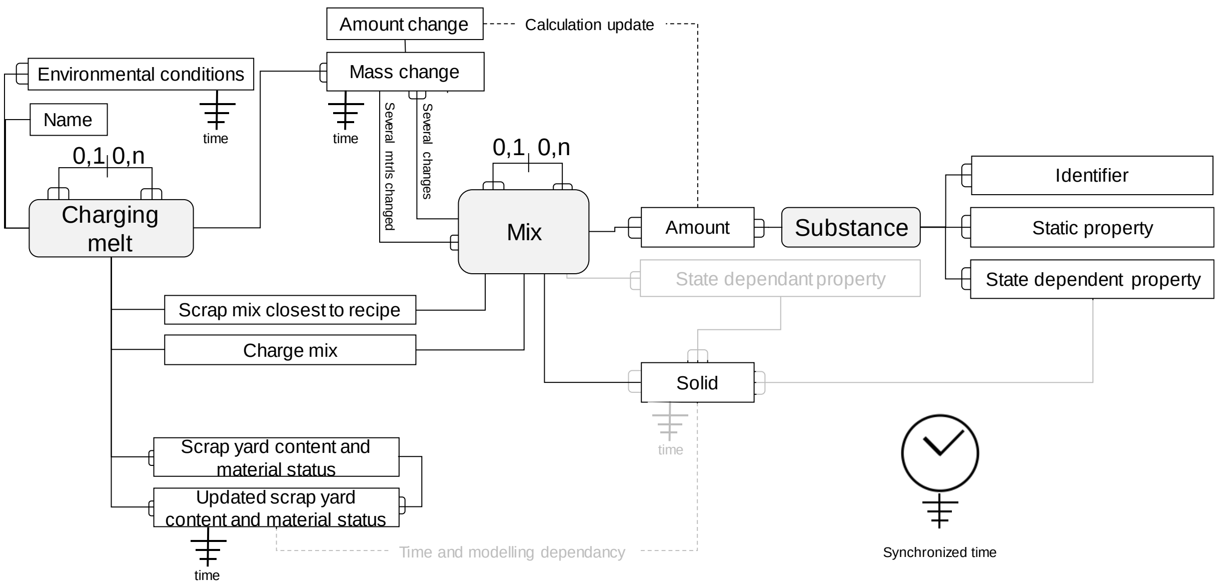


Figure 8. Concept model to dynamically describe the substance mix charged into the melt.

Charging melt – a selection of different substances added to the Mix.
Mix – a selection of substances added to the alloy mix.

2.3.4. Data model requirements: Melt

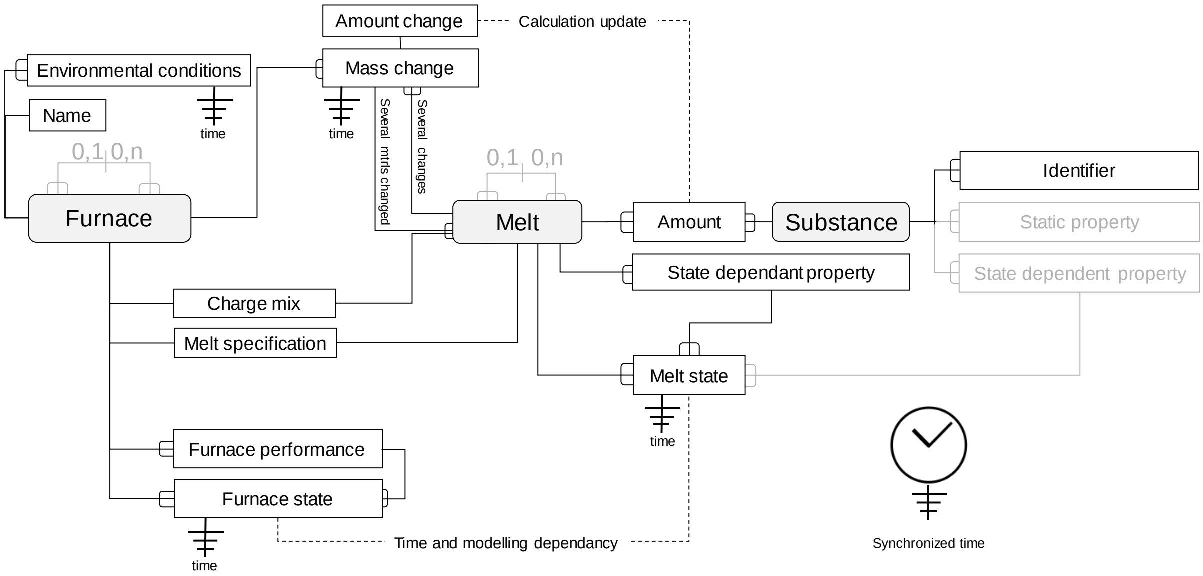


Figure 9. Concept model to dynamically describe the melt as charged with energy from the furnace.

Furnace – the provider of melting energy and energy losses.
Melt – the properties of the melt as it is subjected to the energy of the furnace.

2.3.5. Data model requirements: Ladle

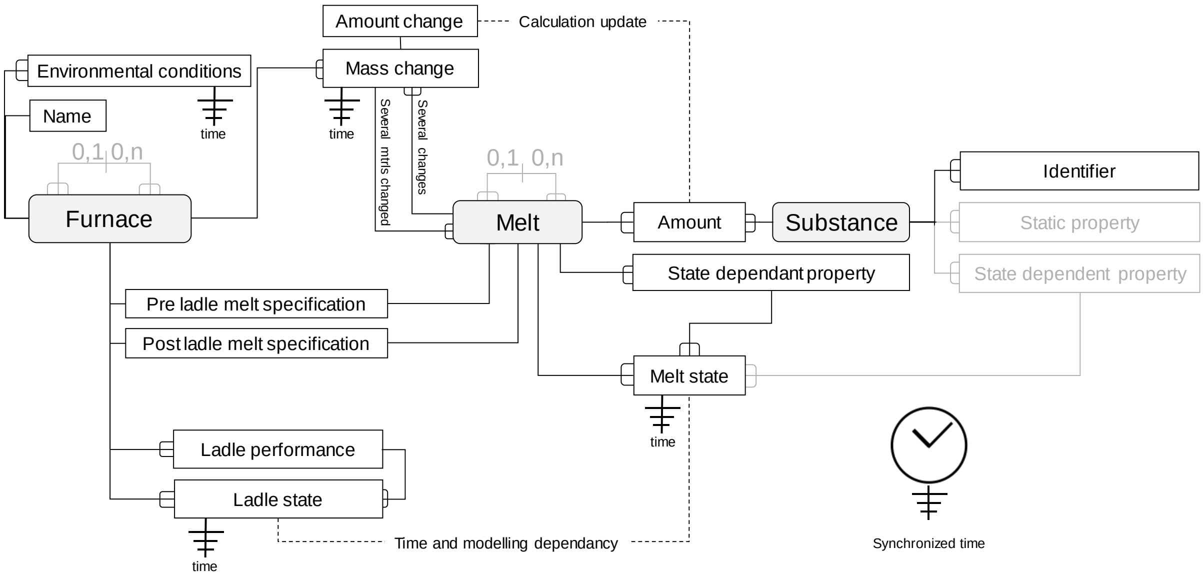


Figure 10. Concept model to dynamically describe the melt when kept in the ladle.

Furnace – energy source and sink to keep the melt at stable temperature.
Melt – the properties of the melt as it is subjected to time and energy, and to addition and removal of e.g. alloys and slag.

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2.3.6. Data model requirements: Mould fill

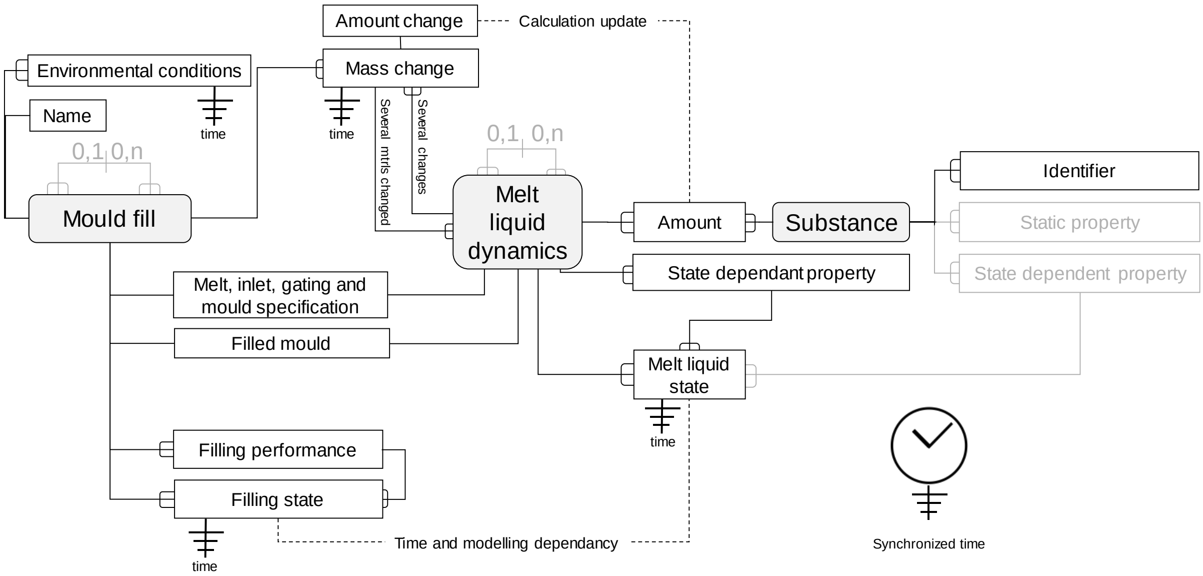

Figure 11. Concept model to dynamically describe the melt is poured into and inside the mould.

Mould fill – The mould being filled.
Melt liquid and dynamics – the liquid and fluid dynamics of the melt.

2.3.7. Data model requirements: Cooling and solidification

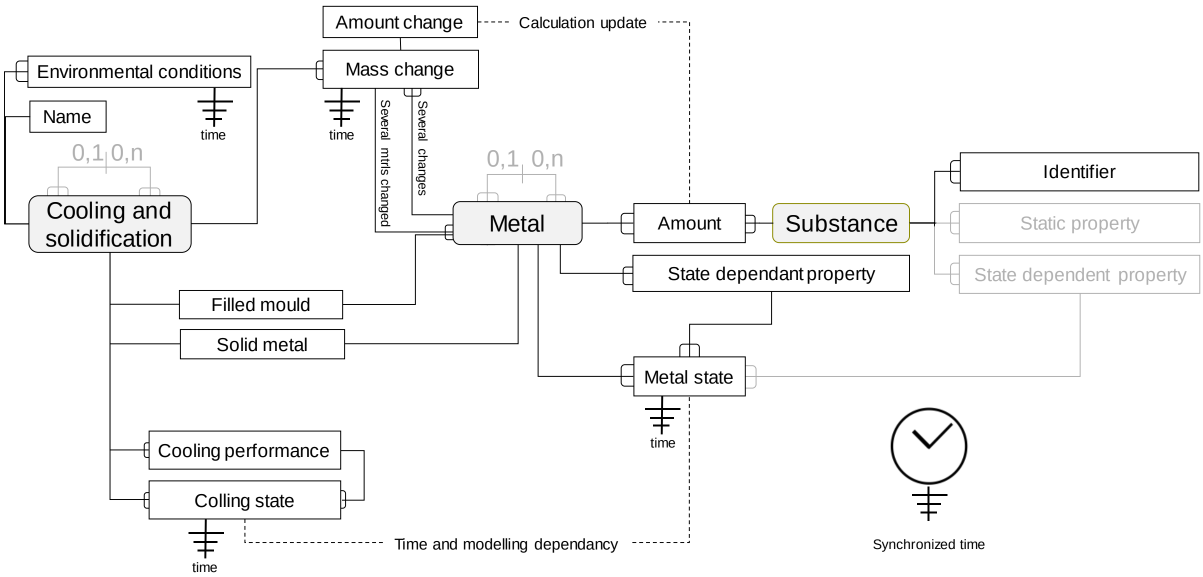

Figure 12. Concept model to dynamically describe the cooling and the solidification inside the mould.

Metal – the metal through its different states from liquid to component.
Cooling and solidification – the energy and material properties of the mould.

2.3.8. Data model requirements: Cleaning

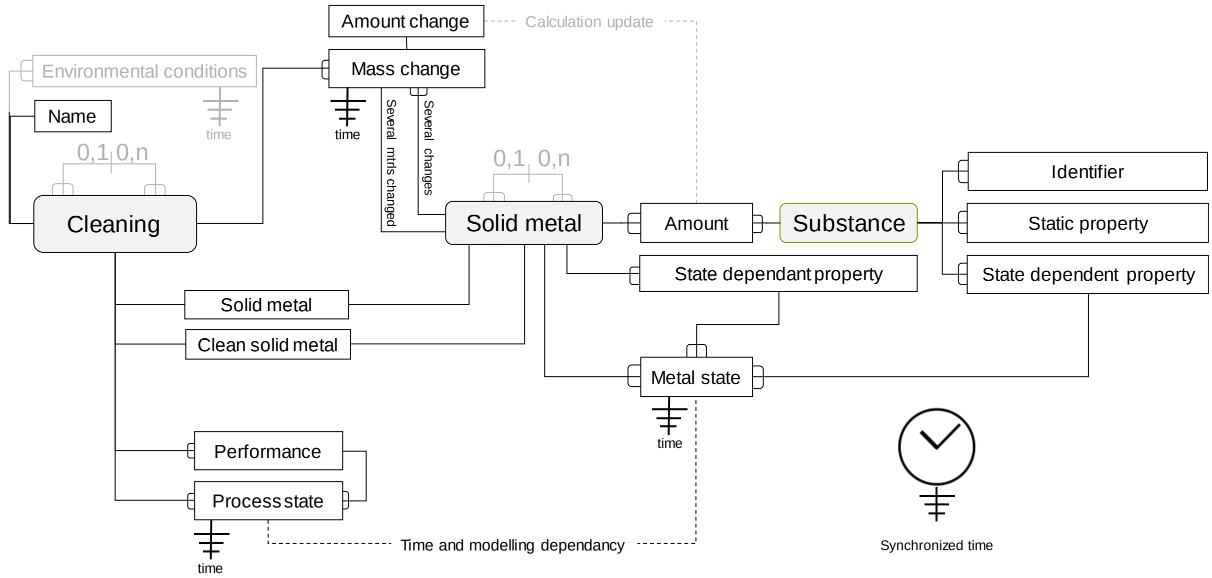

Figure 13. Concept model to describe the cleaning to acquire the solid metal.

Solid metal - the solid metal as shaped by the casting in the mould.
Cleaning – the procedures used to remove sand and slag.

2.3.9. Data model requirements: Post processing

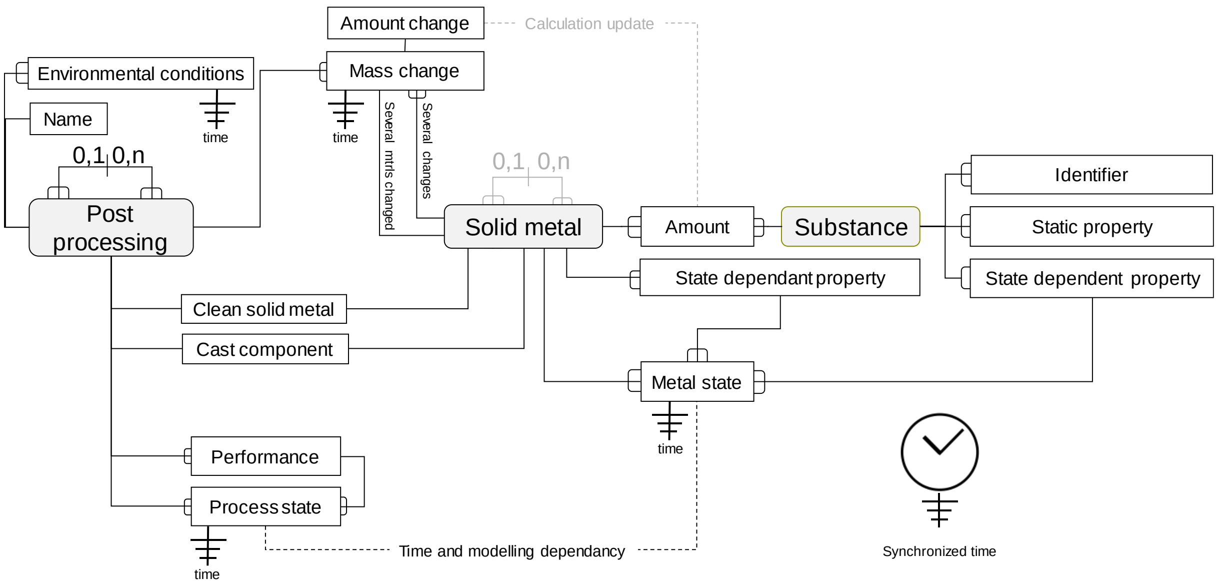

Figure 14. Concept model to describe the post processing to achieve the specified component.

Solid metal - the solid metal as shaped after the post processing.
Post processing – any processing that are made to finalise the solid metal into the specified component.

2.3.10. Data model requirements: Component specification

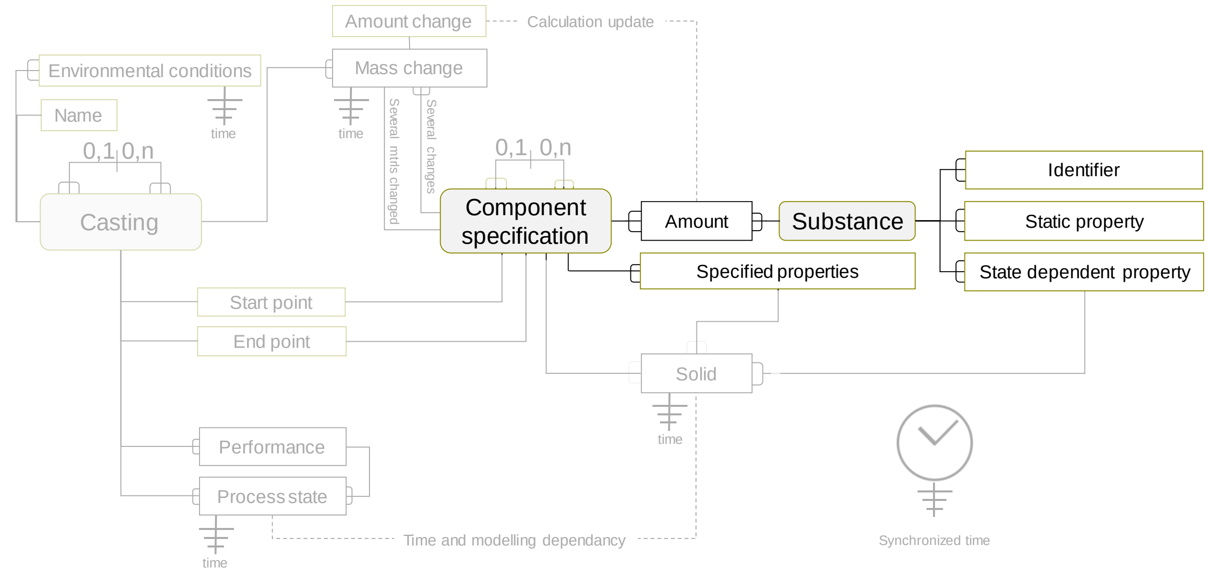

Figure 15. Concept model to describe the component specification.

Component specification - all aspects of the component that can be used to design the entire casting process, from mix to post processing, and that can also be used to verify whether the specification is met.

References

ISO 14033:2019 – Environmental management – Quantitative environmental information – Guidelines and examples