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RELATING ARCHAEOLOGICAL *CHAÎNE OPÉRATOIRE* AND PROCESS MINING IN COMPUTER SCIENCE

1. Introduction

This paper investigates the potential for close methodological synergies between the concepts of *chaîne opératoire* and cross-craft interaction, on the one hand, and an alternative use of the so-called process mining in Business Process Modelling (BPM), on the other. We use process mining and *chaîne opératoire* as an initial ground to bring archaeology and computer science closer. We suggest new theoretical models and methodological approaches fostering cross-fertilization between archaeology and computer science, thus showing how two different disciplines can learn from each others' approaches, both on a theoretical and practical level.

A fruitful collaboration within the larger "Tracing Networks" project is the development of ontologies to structure the multiple data sets, collected by the archaeologists, into a logical complex entity that goes beyond the traditional database structure (Hong *et al.* in press). We are not the first to advocate the use of ontologies for archaeology (see e.g. Aiello *et al.* 2007; Dallas 2009), but our project stands out for its scale and scientific objectives as it includes a number of archaeological subprojects that span from the Mediterranean region to Britain and from 1500 BC to 200 BC. Moreover, ontologies have a twofold role beyond their traditional use in archaeology. First, they provide the ground for cross-cutting research among the archaeological subprojects (e.g., offering the possibility of integrating and querying information on different materials) and, second, they formalize the concept of *chaîne opératoire* and cross-craft interaction. We contend that this approach yields novel insights in both disciplines. In particular, the notions of process in computer science can be formally combined with the archaeological notions of *chaîne opératoire* and cross-craft interaction. A fruitful side effect is the formalization of general archaeological concepts like the notion of artefact.

The present paper gives an account of cross-cutting research inspired by these methodological approaches; we investigate here our common methodologies and test them in case studies based on pottery making. Our case studies on "pottery making" refer to the craft in general terms rather than to specific archaeological "pottery" studies for reasons explained within this paper below.

2. Historical overview of past synergies

Since recently, the project "Tracing Networks: Craft Traditions in the Mediterranean and Beyond" (2008-2013)[1] combines research in archaeology and computer science to explore ancient and modern networks. Although acquainted with multiple software applications, many archaeologists consider computer science in terms of how it can serve their own research or facilitate their professional and social network building. Huggett (2004, 81), for instance, suggests that archaeologists (still) see computers mainly as a tool, and they, thus, do not really investigate or reflect on how computer science has influenced and changed the discipline. This may well be the result of the post-processual reactions against the initial optimism people in archaeology had towards computing in archaeology (Shanks, Tilley 1993, 245). These past processual approaches were useful but had their own limits.

Nevertheless, many more computer applications are now available to us all (see Dallas 2009, 205 for a brief overview). For instance, Gardin and Roux (2004, 25) report on the progress in knowledge spread via the media of websites (referring to Gardin's earlier work) and show little input from the humanities while a network component between scholars and/or institutions is present. The aim of their *Arkeotek* project is to facilitate publishing of archaeological data in a more accessible manner whereby costs are reduced and data overload is tackled so that researchers can navigate easier through a mass of publications (Gardin, Roux 2004, 36).

Already in the 1990s criticism of the Artificial Intelligence (AI) systems (see Gardin's earlier work of the 1970s and 1980s) was expressed. Archaeologists questioned whether they should convert narratives into structures since this can result in the loss of important contextual information. Stutt and Shennan (1990, 766) proposed a different approach by presenting their *WORSAAE* project. However, both *Arkeotek* and *WORSAAE* rely on computer scientists to facilitate archaeological goals; they do not collaborate with mutual benefits in mind. Stutt and Shennan (1990) point out, referring to Shanks and Tilley's 1987 paper, that finds have by nature polysemous meanings, for archaeologists and for people in the past. Again, is converting narratives into structures, then, not too limiting? Stutt and Shennan (1990) suggest the combined use of AI and hypertext to indicate which processes and interpretations are linked to disentangle the strands of interpretations leading to the "final" interpretations based on a set amount of data and work time. While they try to refrain from posing limits to archaeological argumentation, this straight jacket, in fact, sneaks in through the backdoor by their wish «to provide a semi-formal language for the recording of conflicting opinions and

[1] http://www.tracingnetworks.ac.uk/.

their justifications» (Stutt, Shennan 1990, 768, 776). The question, though, is whether language can be formalized, wholly or partially, since researchers have personal styles in expressing themselves which is even more pronounced when archaeologists come from different epistemological backgrounds and have different first languages. Such language formalization, partially or wholly, may affect creativity, on the one hand, while it may also bring home the difficulty of defining the concepts we work with.

Dallas (2009, 205-06) redresses yet another issue, namely the fact that past (from 1950s onwards) researchers employing algorithmic strategies offered both theoretically and methodologically significant contributions to archaeological research relating to the development of instrumentation which, in turn, aided in the development of typologies and the categorization of archaeological artefacts. He states: «Their seminal contribution in problematizing established notions of archaeological data constitution, description, style, archaeological typology, and the construction of archaeological knowledge, prefigures recent theoretical developments and can offer valuable perspectives to current research challenges in digital heritage and material culture theory» (Dallas 2009, 206).

He (esp. 2009, 212-216) thus argues that computer sciences have had an influence on archaeological practice beyond the construction of mere databases, number-crunching and categorization of archaeological materials, resulting in, for instance, the use of ontological systems[2], addressing both semantic and syntactic issues. He sees archaeological computing as socially embedded (Dallas 2009, 217) and encourages the necessary epistemic information of digital curation of cultural heritage by researchers in archaeology. While this redressing was needed, it still shows, however, the usefulness of computer sciences to archaeology as a purely one-way direction of influence, rather than a mutually beneficial relationship.

3. Questions and methodologies

Recently, Brysbaert (2011a, 2011b, 184, and in press) argues that in employing the concept of *chaîne opératoire*:

1- one should allow dendrogram structures and cyclicity and
2- one should allow compositionality to feature in generic *chaînes opératoires*.

Briefly, the generic *chaîne opératoire* (Leroi-Gourhan 1943-1945; Schlanger 1994; Pfaffenberger 1998; Dobres 2000, 2010) can be defined as a series of steps necessary to transform raw materials into finished products, including material procurement, production, transportation, distribution, consumption, discard, reuse, and final discard.

[2] http://www.tracingnetworks.ac.uk/content/web/collaborative_system.jsp.

To motivate the above contention one could consider, for instance, the field of Aegean Bronze Age where most technologies and processes related to pre-industrial crafts seem well understood. Recent investigations, though, have shown that many crafts were linked with each other and that social interactions in palatial and post-palatial (such as at Tiryns in the Late Bronze Age c. 1370-1080/70 BC), and other contexts may have underpinned technological transfers of materials, techniques, and recipes. As argued in BRYSBAERT, VETTERS (2010, 25), knowledge about such complex interactions is lacking. Therefore, the detailed study of the Tiryns material culture at a micro- and intra-site level investigates the interaction, technologically and socially, between people within their societies, and how these interactions may be crucial in forming social identities within larger cross-cultural contexts. By focusing on the small-scale localized interaction between people at Tiryns[3], BRYSBAERT, VETTERS (2010, 26) also aim to find out more about localized networks that may have been present at different chronological stages.

Based on reading Leroi-Gourhan's original publications and agreeing with him, BRYSBAERT (esp. 2011b) argues against the acceptance of *chaîne opératoire* as a linearly ordered sequence of activities and indicates the potential, both theoretically and methodologically, of allowing the *chaîne opératoire* to be interpreted more broadly. The *chaîne opératoire* does not just represent a technical series of steps since this takes place essentially via human hands, and thus implies social processes and procedures as well as technical ones (see also DOBRES 2000). Practically speaking, a generic *chaîne opératoire*, such as metal working, may not be reconstructed from a single archaeological data set since most past technological processes are by nature only partially preserved in the material archaeological record. Gaps in this material record, and thus in the subsequently reconstructed chain, may be filled by extrapolating from multiple data sets that complement each other. As such, they may not come from the same context and, therefore, need to be treated cautiously when applied to specific contexts in which such a generic *chaîne opératoire* may be applied to (e.g. metal working in the Laurion silver mines in the 4th century BC).

Cross-craft interaction (e.g. MC GOVERN *et al.* 1989) entails the nodes of connection, both technical and social, through human interaction, where two or more technologies or crafts meet, exchange recipes, knowledge, approaches, materials, equipment, tools or simply ideas. Cross-craft interaction, furthermore, either welds, solders or rivets multiple *chaînes opératoires* together, depending on how strong each link is (BRYSBAERT 2007, 2008, 2011b).

In computer sciences the term "workflow" denotes the «computerised facilitation or automation of a process, in whole or part» (Workflow Management Coalition). In this context, a process is executed according to a process

[3] http://www.tracingnetworks.ac.uk/content/web/cross_craft_interaction.jsp.

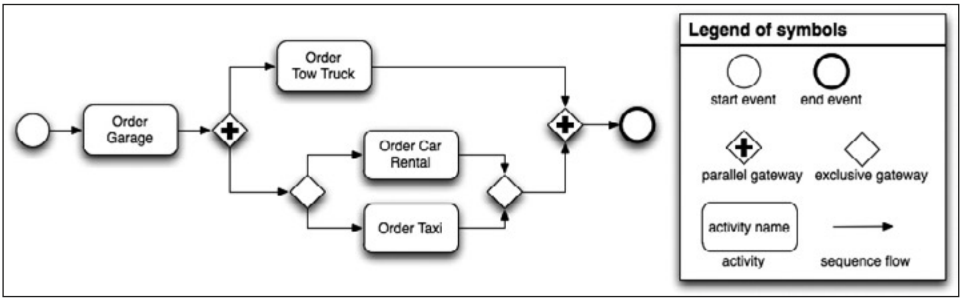

Fig. 1 – A process model for "engine failure rescue centre".

model which dictates how several actors organize their activities. Each activity consists of the execution of a task. Workflow patterns (van der Aalst *et al.* 2003) are widely used to describe the coordination among the tasks of complex systems. The concept of process often has a prescriptive connotation, as it describes how tasks should be executed.

We model processes using the Business Process Modelling Notation (BPMN), a widely used notation for process models of Workflow Management Systems (WfMSs). The BPMN control constructs employed in this paper are illustrated through the example in Fig. 1 adapted from Bocchi *et al.* 2010. The example describes the process of handling a rescue request from a damaged vehicle. The process starts by booking a garage to repair the faulty vehicle, then two activities are executed in parallel: a tow truck is contacted and the search for an alternative transport for the passengers starts; such search takes place for two alternative activities (either a rented car or a taxi). The process is completed when the execution of both threads ends.

A set of techniques falling under the concept of process mining (Weijters, van der Aalst 2001) has been introduced to "extract" process models from data sets consisting of the execution logs of activities over a period of time. Process mining has been described as «the method of distilling a structured process description from a set of real executions» (van der Aalst, Weijters 2004, 232). The goal of process mining is to gain new insight of actual flows of events within a context or organization, when the underlying process model is not (or partially) known *a priori*.

Methodologically, we propose to adopt a formal approach inspired by the computer science notions of workflow and process mining. These notions have to be extended in order to model the complex *chaînes opératoires* envisaged by Brysbaert (2011b, in press). As shown later, this will be done by means of suitable ontologies.

4. Processes in archaeology and in computer science

The next sections illustrate the connection between the notions of process in archaeology and computer science. In Section 4.1 we identify the relationships between *chaîne opératoire* and process models. Section 4.2 expands such relationships to cross-craft interactions and workflows. Section 4.3 links the concept of *chaîne opératoire* to the notion of process execution inspired by computer science processes, whereas Section 4.4 shows how societal aspects of *chaîne opératoire* parallel recent computer science methodologies in process mining.

4.1 Chaîne opératoire *and process model*

There seem to be similarities between the concepts of *chaîne opératoire* and that of process model, on the one hand, and between process mining (see Section 4.4) and analyzing archaeological and related data towards interpretation, on the other. The archaeological data sets correspond to "object-based" execution logs (along Fahland *et al.* 2011). However, the *chaîne opératoire* may rely on "action-based" information inferred by e.g. ethnographic or experimental archaeology data sets. In fact, by its very nature, archaeology may extract data from "objects" from which "actions", and hence "executions", can be inferred only.

A *chaîne opératoire* tends to be associated with one craft while this is not necessarily the case for a process model. The latter may be only partially known *a priori*; similarly a contextualized *chaîne opératoire* is usually partially known (for instance, a pot shaped of raw clay may be coated with slip and fired). Each *chaîne opératoire* construction based on archaeological and other data may then refine a more generic *chaîne opératoire*.

We show how a generic *chaîne opératoire* can be represented as a process by considering the steps involved in pottery making. These consist of: dig, wash, and purify raw clay, mix it with filler, kneed the clay, shape it (on the wheel) into a pot, air-dry pot to leather-hardness state, make and fit on handles, "paint" (in clay slip) patterns on surface, fire pot, allow kiln to cool down and remove pot from kiln. The BPMN process of such a generic *chaîne opératoire* is illustrated in Fig. 2, where for simplicity some steps are omitted.

Note that the collection of the materials (raw clay digging and filler collecting) is done as parallel activities; also, the activity "fitting handles" is optional but must take place after mixing clay and filler and before firing.

4.2 *Cross-craft interaction and workflow systems*

A clear relationship between the concepts of cross-craft interaction and workflow can be established. In fact, the activities of a process may produce, modify, and use different documents, database entries and other types of information. The dataflow – the flow of information in a process – underneath the process in Fig. 2 has not been explicitly represented as it is immediate: each

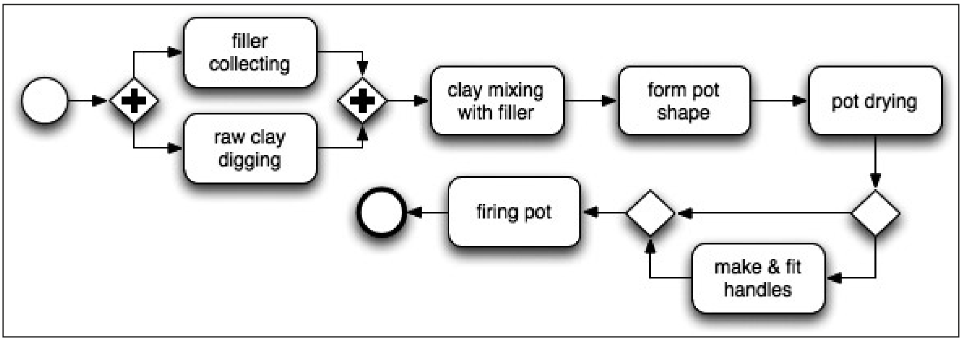

Fig. 2 – A process model for "pottery making".

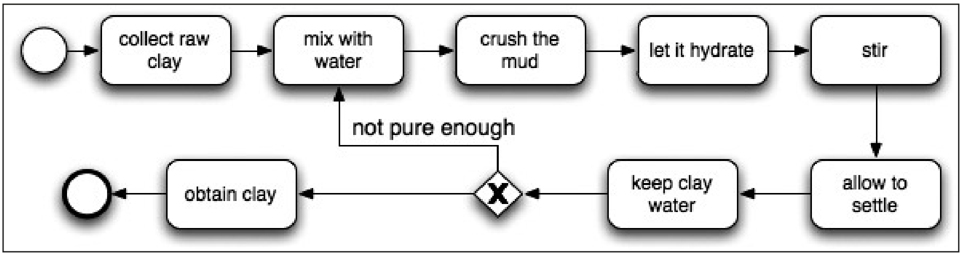

Fig. 3 – A process model for "clay collection".

activity takes an "object" from the previous activity (a more or less elaborated material) and forwards it to the next activity. In a workflow system, several processes may run simultaneously, not all of which may cross over. Some processes will (e.g. making pots, slipping different surfaces), however, and cross-craft interaction indicates how several actors within processes that do cross over organize their activities across multiple processes.

There is a possible cross-over between the *chaîne opératoire* of pottery making and that of raw clay collection (Fig. 3), leading to cross-craft interaction. For example, the activity "collect raw clay" of the process in Fig. 3 produces "residues" and "clay" which can be used in activity "clay mixing with filler" in the process of Fig. 2.

4.3 *Control flow, immaterial steps in the operational chain(s), and social aspects*

In computer science the process model relies on the notion of control flow to relate activities and actors. More precisely, the control flow determines, at each stage of the computation, who is executing what and when. A counterpart in archaeology is not obvious since the traditional usage of the term *chaîne opératoire* (see Section 4.1) emphasizes activities rather than actors (but see Dobres 2000; Brysbaert 2008, 2011b). Instead, the control flow would emphasise the social human aspect of decision-making, organizing activities, and, by establishing rules, it ensures that the process is efficient and remains operative (Reijers *et al*. 2008).

These immaterial steps are paramount but often not represented in the *chaîne opératoire*. In the practical context of a pottery workshop where several people may be at work, for instance, the decisions taken by the master potter are crucial when assigning tasks to workers. The master needs to organise human and material resources, think about who serves best for a given task (experience, speed, hierarchical precedence, skill), and optimize the work so that no resource is misused. The organisation of the Greek red-figure pottery workshops of Athens offers a good insight of specific organised task divisions whereby potters seemed to have owned the workshop and employed painters (who could be slaves or metics or even potters themselves) to finalise the produce (e.g. Scheibler 2002, 1147-1148).

Badly coordinated teamwork would have both technical and social implications and wrong decisions may lead to inefficiency and poor quality. For instance, if two apprentices were instructed to add filler to the same clay mixture (when only one should have done it), this would render the clay-filler mixture useless, introduce inefficiency, and require extra activities to remove the wrong mixture. Finally, apprentices may learn wrong techniques, and the master's social status may be affected (in the eyes of the apprentices and consumers), due to poor organization in his/her workshop.

Decision-making, organization and coordination of human and material resources are all steps in the workflow, the control flow, and are immaterial, thus invisible in most archaeological *chaînes opératoires* (Brysbaert 2011a). Nevertheless, without these immaterial steps, the operational chain would not be operational, and major mistakes would take place constantly, with important technical and social implications. The dichotomy between the expressed material and the invisible immaterial technologies is no longer viable if we try to comprehend the entire operational chain and the many intersecting ones. In archaeology, therefore, we can learn from the concept of workflow since it parallels the immaterial steps in each *chaîne opératoire*.

4.4 *Logs, process mining, instance, and enactment*

The notion of log is paramount in process mining. A log represents a set of instances of execution. In their simplest form, logs are sequences of observable events, for example, in the workflow of a hospital that involves three tasks: check-in, treatment, and payment. These tasks, executed sequentially, are repeated each time a patient accesses the facility; each execution forms an instance of the process. Tab. 1 shows a log recording two instances of the process executed to serve two different patients.

Instance	Activity	Timestamp
1	check-in	31/01/12:8.00
2	check-in	31/01/12:8.20
1	Treatment	31/01/12:8.25
1	Pay	31/01/12:9:00
2	Treatment	31/01/12:9.10
2	Pay	31/01/12:9.30

Tab. 1 – Fragment of an event log in a healthcare scenario.

Process mining extraction relies on the assumption that each event which is sequentially recorded refers to an activity, and is associated to a single instance. It is also assumed that events of an instance are related (in Tab. 1 the first, third, and fourth entries are related).

In archaeology, it is unrealistic to assume such a fine-grained relationship between events because archaeological data may lack the information on specific events. For example, in any given pottery workshop, one can hardly determine the relation of a specific scraper tool with the specific pot whose unfired clay walls were thinned with that scraper. Rather one could potentially relate a number of scrapers with a number of pots found in nearby locations, but only if the pottery workshop preservation conditions were optimal, for example, if the workshop was abandoned suddenly while the vessel thinning activity took place and was then immediately sealed as a context (e.g. by a large destruction). In fact, a coarser notion of instance occurs in archaeology, since the same generic *chaîne opératoire* may have been implemented in different contexts. As such, sets of organized activities following similar patterns may have been observed in different times and locations. A good example is provided, in abstract terms, by Hasaki (2002, 263) who discusses the phenomenon of itinerant potters who may build kilns in each place they work, thus, each time in a different location, somehow starting and running through (thus repeating) the same or similar generic *chaîne opératoire*.

We discern between the fine-grained notion of instance used in process mining and the coarse-grained notion of instance which we call enactment when mining an archaeological log. More precisely, an instance is a single (conceptual) run of a *chaîne opératoire*, e.g., "manufacturing pot *a*", "manufacturing pot *b*", while an enactment is the whole of repeated executions of a number of instances of one *chaîne opératoire* in a specific context, e.g., "manufacturing pots in location *x* and time *y*" is an enactment of the generic *chaîne opératoire* "pottery production".

Depending on the type of information that one intends to mine, other information may be required in the logs. To study the underlying organizational structure of the roles involved in the activities and to derive sociograms illustrating the relationships between actors, the logs should carry information about the actors (van der Aalst *et al.* 2005). A similar situation may be extracted from archaeological data whereby crossovers of different crafts may appear, especially if textual information is available. As already hinted at above (Scheibler 2002), certain pottery workshops in the Classical period in Athens, for instance, are known to have been split up in potters and painters (textual evidence on the pots) and they necessarily met and worked together (Robertson 1972, 180-183; Sparkes 1991, 65-68), therefore, most likely also exchanged information, both professionally and personally. Process mining thus fits very well with the archaeological practice of attempting to compose the entire generic *chaîne opératoire* of pottery making based on:

1- studying pottery (shape, style, decoration, manufacture techniques, clay recipes),
2- studying kiln structures (both from the same period or ethnographic ones), and
3- observing contemporary potters in action.

5. Discussion and results

Section 5.1 re-elaborates specific logs and shows that new notations for archaeological processes and algorithms are needed. Section 5.2 shapes the requirements for an ontology of (workflows for) *chaînes opératoires*.

5.1 *Extending process mining*

The notion of "event" in operational chains – and correspondingly, the type of entries – is more complex in archaeology than in usual computer science logs. This implies that the computational problem of extraction (Mans *et al.* 2008) of a process model for archaeological logs is more complex than for computer science logs. In fact:

1- the entries in an archaeological log are the representation of different kinds of material data (objects, installations, residues) related to the original process, and external data such as texts (if any), experimental data (material ones and log recordings), and ethnographic data (logs on observations and interviews);
2- archaeological logs build on a coarse-grained notion of instance and it is, therefore, not possible to establish a one-to-one mapping of events;
3- time-related information may not be very accurate;
4- the interpretations of archaeological logs aim to capture multiple perspectives (cross-craft interactions, relationship between more *chaînes opératoires*, interdisciplinary triangulation).

Basically, a coherent organization of tasks cannot, in most cases, be directly inferred from the log. Rather, the process emerges from logs of different types according to the context, the exact meaning/semantics associated to each task, and to the log.

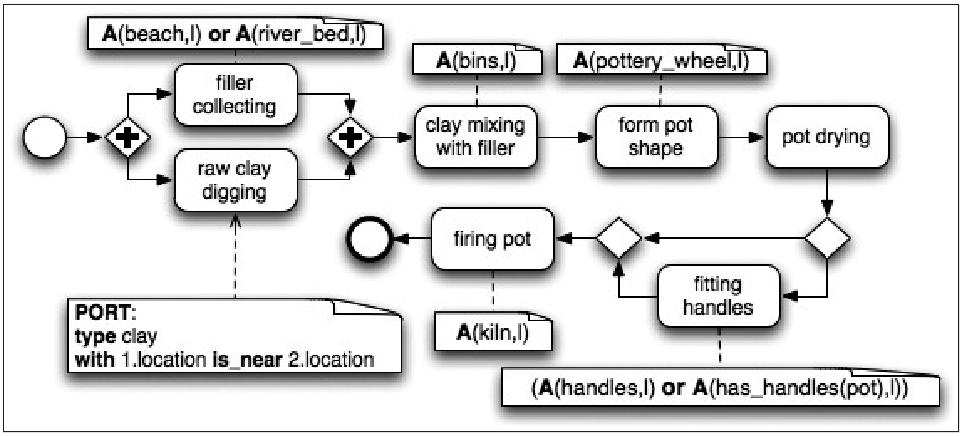

Fig. 4 – Process perspective with annotations: layer 1 – pottery making.

Another computational problem addressed by process mining techniques is conformance checking of a process model with an event log (Mans *et al.* 2008).Whereas extraction does not assume the presence, *a priori*, of any process model, conformance checking can rely on the presence of a process model (hence it is a simpler problem).We show how to solve the conformance problem for archaeological logs representing *chaînes opératoires*. We proceed by discussing the case study of archaeological data for the generic *chaîne opératoire* of pottery production.

We enable the composition of *chaînes opératoires* by extending the BPMN notation with a layered model. A layer represents a process from a specific point of view. In our model, compositionality is featured by means of ports which express dependencies between activities of different layers. An activity can be annotated with a predicate setting the condition the log has to satisfy for that activity to occur.

We illustrate our model by discussing Fig. 4 which extends the process from Fig. 2 with the new annotation. The process model in Fig. 4 focuses on actions (conventionally set as layer 1 which does not include information on the materials, conventionally set as layer 2). Dashed lines associate activities to predicates while arrowed dashed lines link activities with ports. The predicates in Fig. 4 are all instances of:

$A(d,l)$ = exists d such that $x.datum = d$ and $x.location$ is_near l

that checks for the presence of d near location l. For instance, the activity "filler collecting" requires the presence of a beach or a river bed at the context location. Notably, the "clay digging" activity is linked to a port to represent its dependency on some activity, possibly of another *chaîne opératoire*, that provides

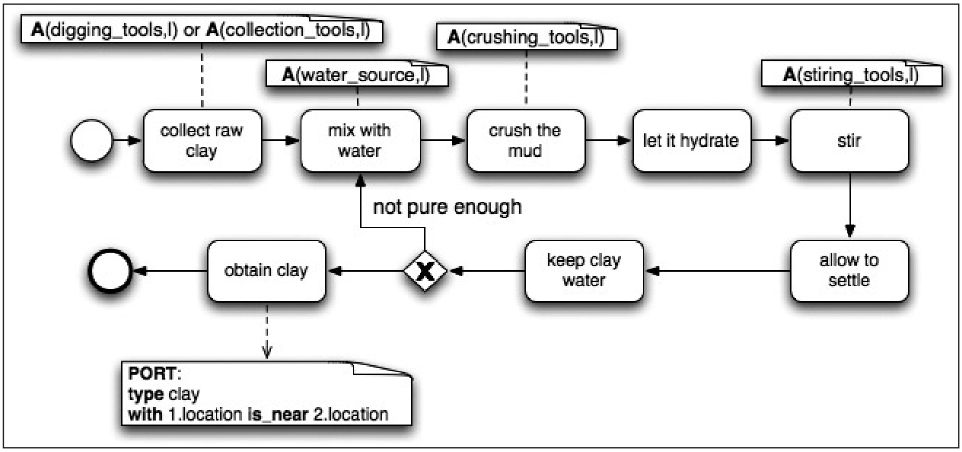

Fig. 5 – Material perspective with annotations: layer 2 – clay extraction.

an object of type "clay". The *chaîne opératoire* "clay extraction" in Fig. 5 (extending the process from Fig. 3) has one outgoing port from activity "clay digging", namely that activity provides clay. Observe that each port also includes a predicate requiring that the location of processes, to be connected to that port, must be in the same or nearby location (e.g., the location of "clay extraction" is the same one as the location of "pottery making", as shown in Fig. 6).

Ports and predicates allow us to compose the processes of the different layers as shown in Fig. 6 where layer 1 consists of the *chaîne opératoire* "pottery making" from Fig. 4, and layer 2 consists of the *chaîne opératoire* "clay extraction" from Fig. 5. The incoming port of activity "raw clay digging" in Fig. 4 has been merged with the outgoing port of activity "obtain clay" in Fig. 5. Recall that the former port models the fact that activity "raw clay digging" relies on an object of type "clay", and the latter port models the fact that activity "obtain clay" provides an object of type "clay". The statement:

"1.location is_near 2.location"

constrains the two *chaînes opératoires* (and therefore the corresponding events in the logs) to be associated to the same or nearby location. Two ports can be merged if their types and constraints are compatible. In this example, the check for compatibility and merging is straightforward since type and constraint are the same in the two ports. In general, the compatibility between ports can be defined in terms of entailment: an incoming port is compatible with an outgoing port if the latter provides all (or more) properties than those required by the former.

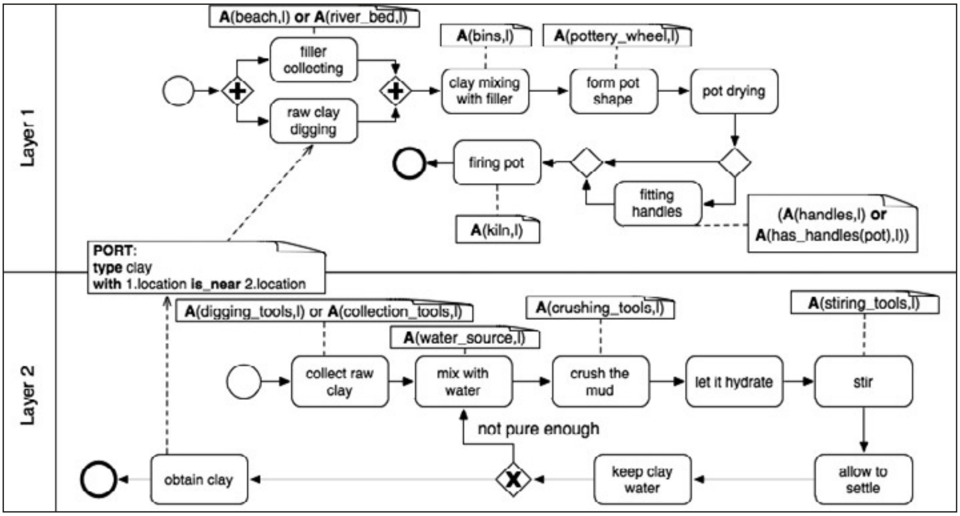

Fig. 6 – Process and material perspective.

5.2 *Engineering ontologies for* chaîne opératoire

The engineering of an ontology for a *chaîne opératoire* hinges on the identification of some pivotal elements and their relationships (Fig. 7). We strive for generality and compositionality. More precisely, we aim to support the wider possible range of *chaînes opératoires* (as well as descriptions at different levels of abstractions), and to define composable ontologies.

We propose to define the architecture of our ontologies around the following concepts:

1- observables
2- causality relations
3- composition of *chaînes opératoires*.

Observables are the tangible elements that give evidence for the operational activities forming a process. In other words, they yield the relevant information one would like to systematize into a coherent workflow of operations.

Chaînes opératoires differ from each other in the relevant information they build on. Depending on diverse archaeological contexts, *chaînes opératoires* are sometimes defined generically or specifically. For instance, the generic *chaîne opératoire* for pottery production builds on the observables described in Section 4.1, while the one for ceramic objects from specific contexts, such as the clay "torch holders" from the Tiryns Lower Citadel IIIB Middle complex require specific observables which may only be applicable to that set of clay

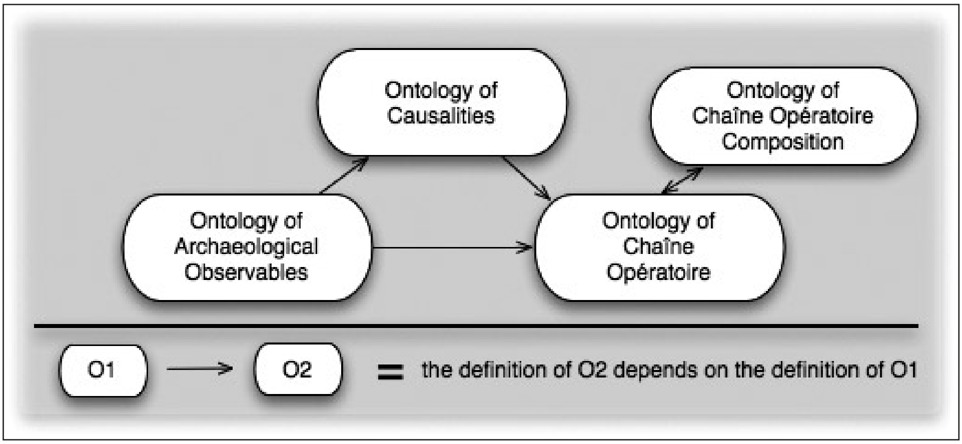

Fig. 7 – Architecture of ontologies.

shapes (Rahmstorf 2008, 111-123 with references; Brysbaert, Vetters, forthcoming). The same counts for the different types of pottery production from Kalapodi, Greece, for instance (Kaiser *et al*. 2011).

In this respect, we envisage the ontology for observables crucial for a generic ontology of *chaînes opératoires*. In fact, the ontology of observables has to represent general as well as specific information. General information can be:

1- archaeological context
2- the nature of the observables (atomic vs. non-atomic, individual vs. social)
3- durability of observables (preservation-related)
4- time/period of observation of the observables, e.g. when the evidence was found and studied[4].

Specific information about the observables is instead depending on two factors. The first, and most obvious one, are the materials needed and the actual type of technology that requires the construction of the *chaînes opératoires* (like those for the generic *chaîne opératoire* of pottery production: clay, potter's wheel). The second factor is related to the "granularity" level of the *chaînes opératoires*. For instance, non-atomic observables (e.g. firing pots) may be refined in a more precise workflow (activities split up in loading kiln, firing under different conditions of presence/lack of oxygen), or a set of observables may be abstracted from a non-atomic observable). Fig. 8 illustrates (the fragment of) an ontology of archaeological observables for

[4] The accuracy of material recovery during excavations and its subsequent study may be of lesser quality when this took place several decades/centuries ago and this may be relevant to past and contemporary interpretations of this material.

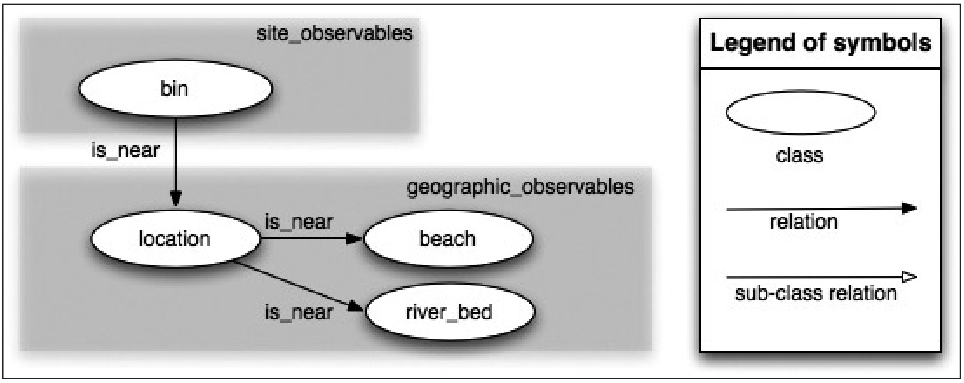

Fig. 8 – Fragment of an ontology of archaeological observables.

the process model in Fig. 4. The observables consist of archaeological findings (top) and geographic information (bottom). Each bin is found in a location, which may be optionally refined to model that the site is near to a beach, to a river bed, or to both (for simplicity, cardinality is omitted).

Fig. 9 illustrates an instance of the ontology in Fig. 8: B1 and B2 are two specific bins which have been found near location 37°58'N 23°43'E, which is near a river bed.

In order to illustrate Fig. 9, a good example of such a real archaeological observable is located, for instance, in the Kerameikos district of Classical Athens where a large double clay "bin" or double cistern containing a thick layer of red potters' clay was found very near to the South of the Eridanos river within the city walls (Knigge 1991, 95). Other clay settling and soaking bins or basins belonging to pottery workshops from the 5th and 4th centuries BC were found further North-East from the Eridanos river in the same district but outside the city walls (Knigge 1991, 163). In ontological terms, Fig. 9 is thus an example of a log that we can use to check the conformance of the process model in Fig. 4, fixing the location l as 37°58'N 23°43'E. The task annotations in Fig. 4 pose the following constraints:

(1) the task "filler collecting" requires the location to be near a beach or a river bed, i.e., "A(beach, l) or A (river_bed, l)", which is satisfied by the log since in Fig. 9 the location 37°58'N 23°43'E is associated, i.e., "is_near", to object R1 of the class "river_bed",
(2) the task "clay mixing with filler", requiring the presence of bins in the location, is also satisfied since B1 and B2 have been found in location 37°58'N 23°43'E.

Causality refers to the nature of the critical relations that organize observables in a coherent workflow. Such relations depend on the (type of)

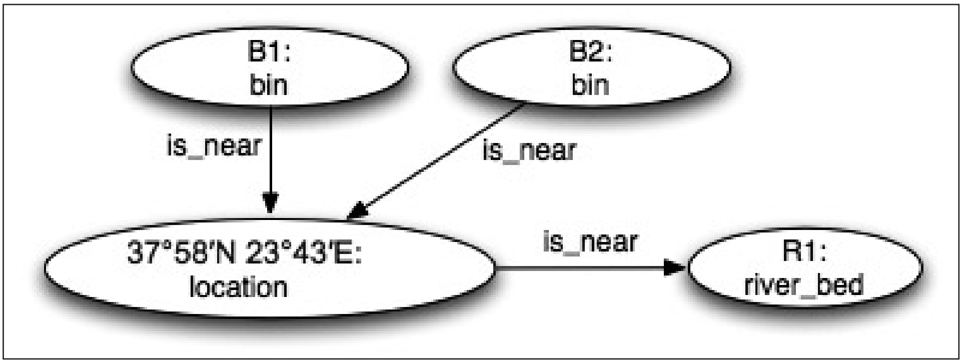

Fig. 9 – An instance of the ontology of archaeological observables.

observables and/or other aspects of observables (for instance, causality relations have to be combined with time/period of observables). In most of the cases, causality relations can suitably be represented as partial pre-orders that have transitive, irreflexive, and asymmetric properties on observables. However, specific *chaînes opératoires* may require more sophisticated or specific notions of causality where an observable simultaneously depends on many, non-comparable others, and whereby the above notions of irreflexive and asymmetric properties may also count. In those cases, it might be appropriate to introduce an ontology of observables and use reification.

Fig. 10 illustrates some possible causalities between the firing/heating and shaping of objects of different materials. These causalities are more general than those in the process model in Fig. 4. In case of conformance checking, these causalities would rule out processes where the task "firing" preceeds "clay shaping". In case of extraction, these causalities provide necessary information for the extraction algorithm to relate the tasks. In fact, without such information, the timestamps of an archaeological log do not allow for a fine-grained temporal/causal correlation between observables. For instance, the timestamps of a potter's wheel and of a kiln can hardly be used by an extraction algorithm to determine whether "clay shaping" occurred before "firing"or vice-versa.

Composition of *chaînes opératoires* is necessary as a more complex structure than mere sequences of steps (see Section 3). This even counts for the generic *chaînes opératoires* (e.g. pottery production, see Section 4.1) and certainly for the specific ones (e.g. Tiryns "torch holders"). This naturally leads to the definition of an ontology to represent an algebra of operations which could capture the structure of *chaînes opératoires*.

Interestingly, this paves the way for the development of a theory of *chaînes opératoires* that allows us to establish formal notions of correctness – spanning

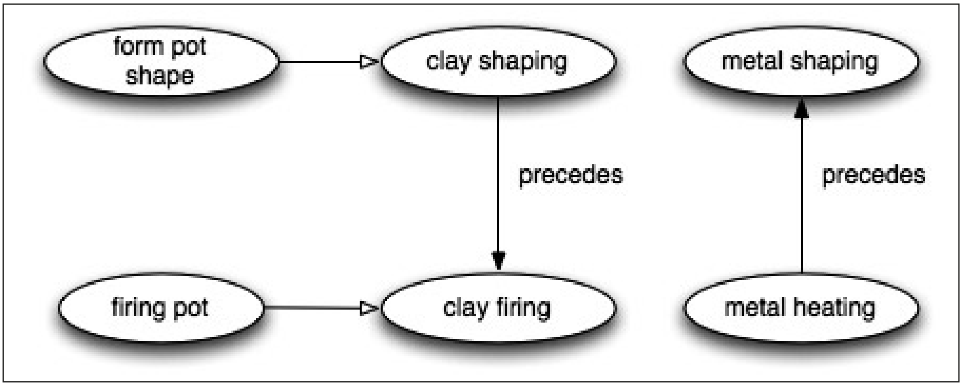

Fig. 10 – Fragment of an ontology of causalities.

from syntactic correctness (i.e., conditions on well-structured *chaînes opératoires*) and semantic ones (e.g., notions of typing or causal consistency) – and to compare and systematize *chaînes opératoires*. These latter possibilities are so far lacking and are urgently needed. A foreseeable positive effect would be the possibility of using our ontology of *chaînes opératoires* (that is its underlying algebra) as a theoretical tool for the development of a theory of "patterns of *chaînes opératoires*". More precisely, by observing structural or type-based properties of different *chaînes opératoires*, one could identify recurring patterns and use them for (a) the enhancement of research on cross-craft interaction which cuts across several independent projects with similar materials (e.g. production of pottery and "torch holders") and (b) the usage of such patterns as heuristics to sharpen process-mining.

6. Conclusions

We advocate the use of formal approaches to systematize the archaeological notion of *chaîne opératoire* in archaeology. Methodologically, this is achieved through the computer science notions of workflow, process mining, and ontologies. Interestingly, our approach highlighted some limitations of process mining and enabled its generalization.

This initial paper introduced the theoretical aspects of our approach using relatively easy and illustrative examples on pottery production. We realize that other materials or crafts may be less accommodating to the ideas expressed in this paper but we also believe that the applicability of a cross-fertilized methodology is a good way forward in order to support our thinking and our practical outputs, to be more systematic about our work while not loosing eye for the social, the unpredictable, and the unknown.

We, next, aim to apply the new findings described and discussed in this paper into a context-specific case study to test them and to investigate the potential influences that these reviewed and refined methodologies may have at the analytical and interpretive steps of the archaeological data processing.

Scope for future work is to overcome two limitations of our proposal. First, some activities in the *chaîne opératoire* – like "pot drying" in Fig. 4 – may have no evidence in the log. It is critical to provide a systematic and rigorous way to model these observed realities, thus preventing incorrect modelling due to faulty expectations on reality when the occurrence of an activity cannot be supported by evidence in the log. Second, timestamps may not provide enough information on the causalities of activities; this must be addressed with new techniques other than the classic process mining ones. For example, if one assumed that all evidence in Fig. 4 is "dated roughly at the same time", this would provide a fundamentally wrong process model where activities are executed parallel rather than in a consistent logical order (pot cannot be fired before it is shaped). Our ontologies engineering approach is instrumental to this but beyond this paper's scope.

Post-processualists may be of the opinion that computer sciences are too positivistic. We argue that this is a misconception based upon the disappointments followed from past high expectations, and the fact that some archaeologists still believe that formalizations limit their intellectual freedom. Ontologies offer the necessary formality while allowing archaeologists to maintain the flexibility they need.

The social aspects of the operational chain play a crucial role, as noted by Reijers *et al.* (2008). In archaeology it is not possible to acquire information through interviewing past actors. However, our approach yields the necessary triangulation as it features compositionality. As mentioned above, the notion of control flow captures immaterial steps like decision-making and organizational steps of workflows. Remarkably, the notion of control flow can capture immaterial aspects of a workflow like decision-making and organizational steps (see Section 4.3). This confirms that in order to grasp as many aspects of entire *chaînes opératoires* as possible we need to abandon the dichotomy material-immaterial, and immaterial steps need to be made explicit in *chaînes opératoires* (Brysbaert 2011a).

Also underdeveloped in archaeology is investigating how many actors worked on specific past tasks and how they intersected. This is at the heart of the "Tiryns cross-craft interaction" project. Measuring numbers of actors involved in specific tasks and, as such, obtaining reliable results with both technical and social usefulness, may be aided by ethnographic and experimental work. A very useful publication, in this respect, appeared recently (Crown 2007 with references; see also on plasterers and painters Brysbaert 2008).

In sum, from this exercise it is clear that archaeologists need to reconsider the terms they employ and be more specific in defining them. What is meant by a *chaîne opératoire* of pottery making: the generic set of technical steps or those specific to a contextualized data set? It clearly does make a difference as this paper has indicated. Moreover, as examples have shown, we need to be much more precise in standardizing our methods of representing our *chaînes opératoires* and cross-craft interaction results in a more structured and accessible way, both verbally and certainly visually.

Two visual representations of a stone tool making *chaîne opératoire* come to mind: fig. 3.1 by Miller (2007, 48) and fig. 4.11 by Bevan (2007, 52). From a computer science viewpoint Miller's chart is closer to a workflow representation while Bevan's looks more like a log. Miller's is more visually developed but Bevan's is more comprehensive in terms of content and our process model approach aims at bringing both somewhat closer together. Miller's chart is not ideal for the following reasons:

1 – There is no distinction made, in the layout of the boxes, between the different types of actions (manual ones or other);
2 – It is impossible to find out whether there are any incompatibilities (in time or space or both) between the boxes which seem to indicate a relative chronological sequence from top to bottom;
3 – There is no indication that possibly some activities may be either linked together, dependent on each other, independent, or parallel.

Process models allow the visualization of the above-mentioned shortcomings. For example, two parallel activities with no cross-overs and done by two independent (groups of) people can be shown clearly through the conventions used in process models. An example of such activities is the plastering and *al fresco* painting done separately, but more or less in parallel by two different groups.

While the dominant perspective of process mining is the control flow perspective (i.e. the ordering of tasks), other perspectives come into play as well, such as information (control and production data such as forms) and organization (i.e. describing relations between roles and groups, allocating both human and material resources to roles and groups, see van der Aalst, Weijters 2004, 237). All these perspectives are analogous to social parts of the *chaînes opératoires* and are of crucial value in establishing the full potential of such *chaînes opératoires* and their analysis, especially when subsequently employed at interpretational levels.

Tight time schedules are not achievable in prehistoric research but by investigating common methodologies with computer scientists for whom time factors are essential to their success, maybe archaeologists ought to try a little harder, and be more optimistic about what some calculations may be able to tell them. Relative dating via pottery typology in, for instance, the Late Bronze Age Aegean, is becoming increasingly refined and this may lead, at least in some contexts, to even tighter time indications in future material studies. Another lack in archaeological studies is addressing "processing time", i.e. the time needed to execute the entire workflow, from start to finish (Reijers *et al.* 2008). In computational research the process log contains timestamps for each event, which, in turn, can help to find, for instance, aspects of causality information, otherwise lost (van der Aalst, Weijters 2004, 233; Fahland *et al.* 2011). Our exercise has demonstrated that if process mining in computer science is to be successful in fields beyond contemporary data logs, existing process mining tools and methods will need to be adapted to fit with the much less and coarser-grained data sets. Archaeology is certainly not the only provider of such coarse data sets. Again, the contextual situation is dictating where adaptations will have to be provided.

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ABSTRACT

This paper investigates the potential for close methodological synergies between *chaîne opératoire* and cross-craft interaction, on the one hand, and an alternative use of the so-called process mining in Business Process Modelling, on the other. We use process mining and *chaîne opératoire* as an initial ground to bring archaeology and computer science closer. We suggest new theoretical models and methodological approaches fostering cross-fertilization between archaeology and computer sciences. The present paper gives an account of cross-cutting research inspired by these methodological approaches and we investigate our common methodologies and test them in case studies based on pottery making. Methodologically, we propose to adopt a formal approach inspired by the computer science notions of workflow and process mining. In fact,, such notions have to be extended in order to model the complex *chaîne opératoire* envisaged by Brysbaert. As shown theoretically, this can be achieved by means of suitable ontologies. Consequently we have re-elaborated specific logs and shown that new notations for archaeological processes and algorithms are needed. In conclusion, we offer a list of requirements for an ontology of (workflows for) *chaînes opératoires*.