S Bødker, M. Kyng, and K. Schmidt (eds.). *Proceedings of the Sixth European Conference on Computer-Supported Cooperative Work, 12-16 September 1999, Copenhagen, Denmark*

Dynamics in Wastewater Treatment:

A Framework for Understanding Formal Constructs in Complex Technical Settings

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Abstract. Based on the study of unskilled work in a Danish wastewater treatment plant, the problem of formalisation of work is discussed and extended to technical processes Five symmetrical levels of dynamics in complex technical work arrangements are proposed as a tool for understanding the limits of formalisation and for designing formal constructs in such settings. The analysis is based on concepts of heterogeneity, granularity of goals and motives, and process and structure.

Introduction

An inevitable problem in the design of CSCW systems is that work is not standing still. Rather, work settings are dynamic: routines evolve over time and unusual situations force deviations from the routine. For this reason, purely formal constructs and descriptions of work have proven inadequate when designing effective, real world CSCW systems.

Suchman and Wynn (1984) set off the debate about the role of formalism in CSCW, and their empirical studies clearly illustrated that there is more to office work than formalised, or formalizable, procedures. Heath and Luff (1992) continue this in their study of work in line control rooms on the London Underground, showing that even seemingly specialised routine tasks rely on peripheral awareness and the participation of others. Thus, impossible to subsume under formal constructs. Bowers et al.'s (1995) study of workflow systems in the printing industry demonstrates their inability to encompass and support the actual course of work. Such systems structure work from without, emphasising inter-organisational accountability rather than the smooth execution of the work. Thus, the CSCW community has succeeded in questioning our ability to completely formalise CSCW.

However, as Schmidt (1997) correctly points out, concentrating only on the non-formalisable parts of work ignores the situations in which formalisation can be a resource and an important tool in cooperative work. He suggests that formal constructs, including written procedures, schemes, charts, workflow systems, and other artefacts, are important artefacts that support CSCW. This is particularly true in the case of complex manufacturing or process plants, where formal constructs, like blueprints or the physical plant itself, are fundamental features. Accordingly, Robinson (1989) argues that CSCW applications must support two levels of interaction, the formal and the cultural. Applications that support one at the expense of the other tend to fail.

Wastewater treatment plants are highly-distributed technical settings. Unlike office-work, the plant operates continuously, independently of the people employed there. Unlike control rooms, risk factors are minimal, since most of the work done at a wastewater plant is not time-critical. In addition, formalisation in wastewater treatment plants both intervenes with the technical aspects of the plant and of the work. Thus a wastewater treatment plant presents a technically and procedurally complex system that differs from the work settings typically found in the CSCW-literature. It is our claim that investigating into the limits of formalisation and the design of formal constructs in the wastewater treatment setting will present findings that add to the previous work of formalisation within CSCW.

This paper reports on our study of a modern wastewater treatment plant in Denmark. The following section describes the plant and its operation and sets the scope for our case study. We then look at different theoretical frameworks that offer ways of analysing the type of work that is wastewater treatment. The next section provides a framework for identifying levels of dynamics in wastewater treatment, based on the theoretical frameworks discussed. With this, we identify five symmetrical levels of dynamics in the case of wastewater treatment plants, on one hand questioning the general formalisability of technical arrangements, on the other hand pointing to a framework for understanding the limits of formalisation in CSCW-design.

A study of wastewater treatment

The case study is part of a long-term research cooperation in the areas of HCI and CSCW involving Danfoss and the Computer Science Department at Aarhus University as well as several other partners. The purpose is to explore the theoretical notion and practical design of common information spaces. The project has focussed on field studies of three wastewater plants, conducted by researchers from the participating organisations. This paper reports on our observations of work at one of the plants. We selected 6 days, within a 5-month period, to follow workers through their entire daily routine. Different researchers followed different workers, using hand-held video cameras to capture the events. We later analysed the video, with special emphasis on the daily work practice, use of artefacts, and how workers dealt with the disruptions. We selected groups of clips to present to the plant employees during feedback sessions and user workshops. We also compared the work practices at this site with data collected by other project researchers at the other wastewater treatment plants.

The wastewater treatment plant

We conducted a study of a modern wastewater treatment plant in Denmark, paying particular attention to how formalisation and flexibility exist in the work practices, and how it affects the coordination of work. The purification process at the plant includes mechanical, chemical and biological phases. The resulting segmented sludge is used to produce gas, which produces enough electricity to run the plant. The remainder is pressed and taken away to an incinerator plant. The plant was one of the first to implement automatic process optimisation for the removal of nitrogen. The automation has been possible due to the development of new sensor technology, which allow for on-line measuring and control of the primary parameters of operation. Not surprisingly, the process optimisation has radically decreased the use of chemicals. The plant has an estimated capacity of 220.000 person equivalents. However, it is constantly running at 110 - 150% over capacity because the plant has not been able to expand to match the increase in the city's production of wastewater.

The work

The wastewater treatment plant employs a total of 8 people. The two managers are responsible for the overall management of the plant. The remaining six employees work in pairs, with the following areas of responsibility:

- chemical test lab, receiving the sludge-trucks, preliminary sorting area, sand trap
- outside plant areas, putrefaction tanks, sludge tanks, gas-turbine building, control room
- sludge press

The three pairs of workers are each responsible for tasks associated with a specific part of the treatment process. Individual workers may temporarily take on other tasks, as when someone is ill, but the overall division labour is quite stable.

Within the bounds of the set of work tasks, individuals are free to 'juggle' the tasks as the situation demands. An important goal of this organisation of the work is to keep the relevant part of the plant in a condition that will allow the underlying purification process to run effectively, even when the worker responsible is home on nights or weekends. For example, the worker in charge of the lab spends two to three hours every morning collecting water samples and sludge and then analysing the quality of the water at different stages of the purification process. The worker in charge of the gas turbine area checks each of the different machines and collects the read-outs of how much gas has been produced during the last 24 hours. The plant manager's area of responsibility is wider, but the tasks are of the same nature. He starts every morning at his computer, getting an overview of the status of the plant by looking at his customised graphs and the lists of alarms.

Although each worker's daily routine of checking and maintenance is highly standardised, there is also a high degree of unpredictability at the plant. The majority of alarms received at the wastewater treatment plant are warnings, such as when the water level is at the maximum limit for a tank. Some alarms call for (relatively) immediate action, while others may be addressed over a period of days. Sometimes the worker can handle it himself, other times an outside specialist must be called. If the alarm is due to machine failure, several workers may completely break off their daily routine and enter into a cooperative problem-solving effort. Workers and managers specifically pay attention to warning alarms and physical signs of problems, since it is much more desirable to prevent rather than recover from machine breakdowns.

The wastewater plant is continuously engaged in a number of experiments to optimise the purification process, to produce cleaner water and decreased costs. Experimentation usually involves introducing new technology or work practices which may provoke unanticipated events and effects on everyday work. Outside visitors, such as school classes, also disrupt the normal routine, even though the visits are carefully planned and executed.

In general, the daily work routine has a dynamic structure. The workers need a deep understanding of the assignments and the plant itself in order to perform their tasks without continuously having to reinvent their work practices. This enables them to place equipment in the area for later use, and allows them to redefine the order of tasks in order to cope with the numerous events that cannot possibly be anticipated.

Perspectives on wastewater treatment work

In the standard engineering literature wastewater treatment is described as a fixed series of well-defined components (e.g. Droste 1997). This analytic perspective is in marked contrast to the plant manager's perspective. He sees things as a result of a historical process, from the first basins built to a prediction as to where a new set of tanks will be added. The former view is static and formal; the latter is dynamic and situated in the current context.

The discrepancy between the static engineering view and the manager's historical conception is no coincidence but rather a result of different needs. The engineer focuses on optimal constellations of technical components, using the fixation of as many variables as possible as an important tool. The wastewater plant manager "lives" in the plant for a longer period. For him the engineer's plan is a starting point, what Star (1986) calls a border condition, among many others, against which running the plant is realised.

Process and structure

Both the systematic, static view and the historic, dynamic view are needed to understand and design technical systems; neither can be abandoned. Thus we need a conceptual framework that can deal with these simultaneously, and the dialectics between structure and process.

In analytical philosophy, process means mere movement, 'a sequence of events' (Blackburn, 1994). In dialectical materialism, process includes the sense of transformation of the given (Israel 1979). With this background, Mathiassen (1981) introduces and utilises an analysis of process and structure as a framework for understanding the development of computerised work arrangements. A model with structure in focus sets limits for sub-processes within the structure, but at the same time super-processes may change the structure. Structure is in this context denote the qualities we perceive as solid or stable but which are changeable. In the same way, a model with process in focus is changing subsumed structures at the same time, as it is itself structured by super-structures.

Mathiassen argues that the choice of whether to focus on structure or process depends on how well-known a situation is with respect to the object of activity, the means for realising the object, the constraints on the object, and the outcome of different actions, or to which degree a situation is *established* or *emergent*. Andersen et al. (1990), also reflect this relationship with regards to system development. In highly established routine situations, a high degree of formalisation is possible because both the problem and the working practice to solve it are known. In problem solving situations where the working practice is unknown, the degree of formalisation is completely dependent on the situation's emergent nature. In problem setting situation, which are highly emergent, formalisation will be counter-productive because neither problem nor means of solving it are known. The degree of uncertainty in a work situation is particularly interesting because its analysis is fundamental to understanding the (cooperative) work practices build around them.

Human activity and the dynamics of collaborative work

The three levels of uncertainty by Andersen et al. (1990) has some similarity with the hierarchical structure of human activity identified by activity theory (e.g. Engestrom, 1987). Where Andersen et al. define levels of uncertainty according to goals and means being known or unknown, activity theory structures human acts according to their motivation and automaticity. Human activity is seen to be mediated by artefacts in a dialectical process of continuos and reflective recreation. Human activity is situated and can only be analysed in its social, historical and technical context. The basic unit of analysis is the connected structure of subject, object, instruments, based in socio cultural context — the activity system. At the topmost level of its hierarchical structure *activity* is motivated, directed to fulfil a need. Activity is realised through conscious *actions* directed to relevant goals. In turn, actions are realised through unconscious operations triggered by the structure of the activity and conditions in the environment.

Within this hierarchical structure, Raithel (1996) propose, a framework for understanding collaborative work, identifying three levels of collaboration: co-ordination, co-operation and co-construction. At the co-ordination level, collaboration is an integral part of routine work. the participants act according to scripted roles, defined by explicit written rules, the division of labour, traditions and tacit knowledge. At the co-operation level, collaboration is directed to a known object (or goal) shared by the actors, but the means are not shared or even known to all the actors. Thus, actors continuously modify actions based on intermediate results, adapting to others' actions and conceptualising their own actions in the process of realising the object. At the co-construction level new motives are created. Neither the object of work nor the means of obtaining it are fixed or shared between all actors. Instead they continuously re-negotiated and re-conceptualised throughout the process to create a commonly shared set of objects and rules. This framework has been used in studies of court cases (Engeström et al. 1991), and in studies of the dynamics of collaboration in hospital settings (Bardram 1998). It can be understood as an elaboration of the uncertainty framework referred to above, pointing to the construction of goals and motives as central aspects of the dynamics of collaboration.

At the wastewater treatment plant, situations connected to breakdowns of machines are examples of co-operation. The breakdown changes collaboration from co-ordination to co-operation. Co-construction rarely occurs at the wastewater treatment plant but may be prompted by external factors like new technology, new environmental legislation or critical changes in the quantity and quality of wastewater from industry and the city. In such cases co-construction primarily involves the manager and people at the city wastewater office.

Identifying dynamics

As wastewater treatment is a dynamic setting with processes at many levels, from water flow to transformative changes of the overall purpose and structure of the plant, it is necessary to develop a detailed analysis of these dynamics. In identifying the dynamics in the wastewater treatment plant we have constructed the following checklist. The checklist is based on the concepts introduced above, and is suggested as a general tool for the analysis of complex technical work arrangements.

- Identify contextual units
- Consider granularity of goals and motives
- Identify processes
- Link processes with the structuring of contextual units
- Identify modes of formalisation
- Identify types of technical structuring

Identifying contextual units

Contextual units are units of the setting that make sense according to specific situations, tasks or purpose; heterogeneous and overlapping. According to Star (1989), boundary objects are objects used by different parties in different localities; robust enough to maintain identity across heterogeneous use, but plastic enough to adapt to the constraints and needs of the different parties working with them. Components of the wastewater treatment plant are boundary objects in the sense that are parts of overlapping contextual units. However, the interpretability is in general somewhat limited. As part of the daily round of one of the workers, a specific gas motor is looked at and listened to, thus part of the contextual unit of the daily round. However, the same motor constitutes it own isolated contextual unit in situations when it is taken down for repair. Further, the motor is part of the subpart of the plant transforming gas in the sludge into electricity. This gas production is a contextual unit from one perspective, but at the same time an important indicator of the load of the whole plant. Another example: the managers office is the centre and symbol of management and general monitoring of the plant, but it is also where one of the unskilled workers daily enters results from the laboratory tests into the process control computer system. The heterogeneity of contextual units is fundamentally different from the hierarchical decomposition seen in the mainstream of engineering literature.

Consider the granularity of goals and motives

A specific alteration of the technical arrangement may appear as a transformation of the basic condition for one activity, while it from the perspective of another activity reflects maintenance of stability. Thus, introducing a new polymer into the wastewater cleaning process, as we saw at the plant, meant some of the workers had to extent their daily work routines to include new tasks. The introduction of the polymer changed their work practice. From the point of view of the city wastewater office, or the plant manager, however, the new polymer was perceived more as an adjustment than as a transformation. Such differences are related to the granularity of goals and motives. In dealing with this granularity we need an understanding of the historical development of the setting, its background and motivation (Markussen 1993).

Identifying processes

As discussed above process can be understood as mere movement in time and space. This notion of process is needed in understanding the technical arrangement of a wastewater treatment plant and in understanding the purification process as such; water flowing, phases oscillating, etc. Human work is another kind of process, possibly highly routinised, like the daily test sample collection round, but always motivated at some level. The question to ask for every process is whether it is causal, according to laws of nature or if it is intentional, dialectically directed by motives. In both cases, the technical structuring of the process, e.g. timing of sample taking determined by phases in the purification process, can be taken into account.

Linking processes with the contextual units

In linking processes to the structuring of contextual units we consider processes structured by the contextual units as well as processes changing or moving the structures of these units. The test sample collection round is structured by the distribution of test sample points around the plant. The arrangement of test points at the plant is changed by the development of new ways of testing, such as automatic sensors, and by new insights and requirements from the society. The process-structure diagrams described by Mathiassen (1981) supports this step, although it doesn't fully acknowledge the heterogeneous nature of the contextual resulting from variability of purpose, and the non-hierarchical features of the technical structure.

Identifying modes of formalisation

The identification of modes of formalisation is primarily related to the work going on in the considered domain, and can be treated in the terminology of constraints and possibilities (Mogensen 1994). In the study of wastewater treatment, it was particularly useful to analyse the modes of formalisation in terms sequentially, enforced or emerged, as well as dynamics or flexibility of routines. Large parts of the work of the unskilled workers at the wastewater treatment plant are formalised by daily rounds at the plant, by forms that have to be filled out. Most of the sequential formalisation at the plant could be rearranged, implying that these sequences serve more as well-structured checklists than scripts. The formalisation in relation to work at the laboratory is less flexible in that the formalisation here is embedded in the tools. Thus, the test tubes must be shaken, heated for 15 minutes, etc. in order to work at all.

Identifying types of technical structuring

The technical structuring is the structuring around the physical, chemical and biological processes as well as the structuring of the process control and automation system. This structuring can be analysed from the perspective of the present paper, limited to the basic considerations of the type of process, as well as from the expert perspectives of the relevant engineering disciplines. As an example, automation theory yields a distinction between the process (water flowing) and the control system, which is particularly useful. A feature of the particular technical structuring of the wastewater treatment plant was the number of false alarms that routinely had to be unset.

Dynamics in Wastewater treatment

The analysis of the case study can be summarised in two issues concerning dynamics. First we propose a five level model of dynamics, secondly we discuss the contradiction between maintenance and optimisation as an instance of the general contradiction between motives of different praxes.

Levels of dynamics

We have chosen the perspective of wastewater treatment work as a (dialectic) correlation between elements of structure and process that on the one hand shapes and delimits but also, and more importantly, has within it the ability to transform and transcend. We chose this view because it supports the understanding we have obtained of the work during the field study, namely as constantly adapting and changing to reflect several levels of other dynamic systems that affect different aspects of the wastewater treatment process. We now try to substantiate this perspective by mapping out the different kinds of dynamics and structures we see present in the wastewater treatment process, and we do this aided by the checklist.

The technical process

The most basic level of dynamics in wastewater treatment, its *sine qua non*, is the movement of water through pipes and tanks and the alternation between phases, of e.g. nitrification and de-nitrification, in the purification process. In the same way movements of people working at the plant is a basic, and obvious, form of dynamics.

People moving around

Large parts of the work at the plant is associated with walking around, often moving through the same, remote parts of the plant several times a day. This is done to collect test samples, but more often just to monitor the condition of the plant and the process, as a vital part of preventing breakdowns and verifying system information.

Technical re-arrangement

During the period of our visits at the wastewater treatment plant, the technical structure of the plant changed. On our second visit, we saw a tank located in a driveway. The tank contained a polymer, an oil-based substance that separates water and sludge, decreasing the percentage of water in the sludge before it is processed in the bio gas generator. This was one of many experiments to increase the wastewater treatment capacity. When we visited the plant three weeks later, a shed had been build around the polymer tank. Thus, the experiment had attained a more permanent status. This example has two implications for the study of dynamics. First, that the technical structure is moving, and that the change may begin as experimental fluctuations and end as sustained change of the technical structure. Second, that movement in the technical the structure, e.g. the appearance of the polymer shed, for the chief biologist at the central wastewater office may be a case of mere adjustment of the established mode of operation For the men at the plant, however, the shed and the new equipment in it was an alteration of the working environment, introducing new tasks in the day to day work, calling for adjustment of established practice, and the building of it was an object in itself.

Flexible routines

One worker, while checking the area around the sludge tanks, noticed that the surface water in the tanks was brownish. He immediately proceeded to the building the water would have come from to check a filter he suspected to be the cause of the water being discoloured, and which turned out to be in dire need of a rinse. He explained that if the water hadn't been discoloured, he would have gone down to check the filter anyway because that building is part of his area of responsibility, but that he would not have done so until much later. This situation may seem too simple to be of interest; one man works alone, going on a well-defined round. However, even though the contextual unit, namely the part of the plant associated with the tasks on the round, both physically and process-wise, and the goals, namely checking up on a number of things on the plant, are well-defined, we see that this situation reveals some interesting points with regards to the identification of modes of formalisation and the process.

Because he encounters the brown water, which we may call a causal process outside of but interfering with his actual work, his motive changes with regards to what needs to be done when and he initiates a change in his routine. Even though the daily round is well defined in terms of which tasks should be done and checkpoints visited, the routine still leaves plenty of flexibility for the reorganisation of the order of tasks. The alternative, which would be to perform the related tasks in a strict sequence, perhaps related to the physical layout of the plant would contradict an overall motive of work at the plant, namely to keep the purification process running continuously. The lack of response to warnings such as the brown water would seriously increase the risk of an actual machine breakdown. Going exclusively by the physical layout also renders the process-look at the purification process invalid, because it becomes impossible to look at connections between the components that are related in the process but not physically standing side by side. Most importantly, though, is that these reservations holds double for cooperative situations. If the workers have to leave their routines to collectively recover from a machinery breakdown, the flexibility is even more crucial.

After arguing that a high degree of flexibility is important in the everyday routines, we would like to emphasise that this is not the case for all aspects of wastewater treatment processes. It would be absurd to claim that flexibility is necessary in the physical flow of the water through the plant, thereby making it possible to send the water out into the bay before the chemical or mechanical cleaning process. This is also why we argue that the technical structure of the wastewater treatment process needs to be identified and juxtaposed with the continuously changing processes.

Transformation of the domain

Some of the most profound changes in wastewater treatment have come from the development of environmental legislation. The water quality plan passed by the Danish parliament in the late 80'es introduced new norms for pollution of water resources. One motive for this legislation was instances of severe extirpation of the fauna in several lakes, rivers and sea areas caused by too many nutrients in the outlet of water from houses, industry, and the primary production. Thus it was no longer acceptable to let 'black' water from the wastewater treatment plant out in the bay, neither legally nor according to public opinion. Depending on the degree of effort necessary for the wastewater treatment plant to reach the new legal level of nutrients, the technical process and the work routines changed in accordance to this; small changes on existing technology would not affect the purification process noticeably whereas the implementation of new technology and a radical change in the tasks performed or the staff involved would more or less completely change the process on a contextual or non-technical level. In the former case we wouldn't talk about the contextual unit of the plant being changed whereas the latter situation would call for a redefinition of several levels of contextual units, possibly including the wastewater treatment system for all of the city. From this example it becomes apparent that we must deal with a whole range of external influences that may affect the wastewater treatment process, possibly quite profoundly. Similar influences could be the consequence of the development of new technology making the purification process more efficient and economically attractive, even though the means for effective purification and economic gain rarely go hand in hand.

Maintenance vs. optimisation

In the following we discuss the tension between maintenance and optimisation as an instance of conflicting motives in wastewater treatment. Throughout our field study we have seen several examples of how the contextual units or work horizons may differ, especially between management and workers. Management and workers share the goal of making the plant run smoothly. Management also has the goal of improving how the plant runs, both economically and in terms of cleaner water. In specific situations, such as when experiments of adding a new polymer to improve the quality of the sludge (work horizon for management) causes the sludge to stick to the canvas in the press thus making it harder to empty it, this disrupts the work of maintaining the sludge press process (which is the work horizon for the workers in the sludge press). These types of disruptions, if not identified and handled, may in the last instance cause collaborative efforts to break down. To aid us in this identification and handling process we find it fruitful to consider two different work perspectives: maintenance and optimisation.

Maintenance focuses on keeping the wastewater treatment system (or parts of it) stable and running without breakdowns. The motive for optimisation is to change one or more processes to obtain a better end-result in terms of cleaner water. So managers may consciously introduce disturbances to optimise the running of the plant, whereas maintenance workers will try to eliminate disturbances and preserve the status quo. When the goal changes over time, the maintenance work changes to reflect this, so stability in this context does not equal a completely fixed state but rather a space defined by the levels of dynamics affecting the wastewater treatment process within which maintenance work operates. Similarly, optimisation work is delimited by the structures within the different levels of dynamics and thus not free to make arbitrary changes. Consequently, the two perspectives contain many identical elements, which makes it hard tell them apart. However, they differ on a few but significant counts, namely with regards to the motive and possibly the contextual unit in a given situation. The proposed framework offers methods for analysing work in relation to motivation and thus helps us assess which perspective is driving the different actors in a collaborative activity.

Conclusion

In line with the mainstream of CSCW research following Suchman's (1986) questioning of formal constructs, our study of the wastewater treatment plant establishes yet another case where deviations and situated action is a hindrance to complete formalisations. Further, we have questioned the applicability of formal constructs in relation to the technical arrangement based on the analysis of the various types of dynamics observed in the wastewater treatment plant, according to their degree of permanent change, motivatedness, and transformative feature.

It can be expected that the general technological development will bring the cost of relevant computer hardware down to a level where it will be feasible to introduce a higher degree of fine masked control technology, sensors, on-line meters, etc. in wastewater treatment plants. Our study points to the likely difficulties in implementing such formal constructs, not just in relation to the flexibility of work at the plant, but also in relation to the process system as such. Because of the dynamics of the technical arrangement, fine-grained control systems will need to be updated at a rate where it is not likely to pay off. For every modification of the plant, for every new polymer tank, the control system may need to be modified. Design approaches enabling technical tailoring based on strong modularisation and encapsulation, or approaches locating parts of the control system in the components, may help; however not when it comes to the more home brewed changes in the process system, and clearly not in relation to the flexibility of work routines.

The proposed five levels of dynamics, as well as the framework for identifying the dynamics, have helped us understand the domain of wastewater treatment. These conceptual tools may also be helpful in the design of CSCW-systems for complex technical settings, especially in handling formalisation and the design of formal constructs. In future activities in the wastewater project the reported analyses of levels of dynamics will be used and evaluated as a basis for design.

Acknowledgements

We will like to thank the people at the wastewater treatment plant, and our colleagues in the wastewater project Also, thanks to the anonymous reviewers for constructive criticism. Finally, we owe a special thank to Wendy Mackay for being extraordinarily helpful Our work on the wastewater project has been supported by The Danish Basic Research Foundation, Centre for Human-Machine Interaction and The Danish National Centre for IT-Research, project no 23 (Usability Work in the Danish Industry)

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