Complexity of Socio-Technical Systems: concept for a uniform metric

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Abstract

For five decades complex socio-technical systems have been studied in an attempt to understand and prevent the occurrence of accidents. In this paper, the authors define a concept for a System Complexity metric, comprising the total of all direct interactions between the system elements and the tools the controller has to control the system. Subsequently, the human performance of the operator is taken into account to arrive at the Perceived System Complexity. Finally a hypothesis for a relation between the dynamic actually perceived system complexity, and the occurrence of incidents is postulated, which are still to be proven in practice.

Keywords: Complexity; Complexity Metric; Socio-Technical System

1   Introduction

In 2017 the Dutch National Research Council for Safety published a report (Onderzoeksraad voor Veiligheid, 2017) on the safety of the air traffic at Schiphol. In this publication, the *complexity* of Schiphol was mentioned as being very high when compared to other airports. This high complexity was linked to the frequent changes of flight approach patterns and the

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simultaneous use of crossing runways, which, in the case of a go-around might lead to dangerous situations, caused by crossing trajectories. Unfortunately, in this report, no definition was given for complexity, nor was a mathematical formulation used for quantifying complexity, and only intuitively a link was made between the complexity and safety through the occurrence of single incidents without proper quantitative validation. This paper intends to present a concept for a complexity metric and a hypothesis for a mathematical relation between complexity and safety.

Since the first accidents with nuclear power plants (e.g. Three Mile Island nuclear power plant accident, 1979), increased complexity of modern socio-technical systems and tight coupling amongst system components and processes have been seen as factors of decreased safety performance due to the limited ability of controllers to fully understand and control such systems and react adequately to unforeseeable situations (Perrow, 1984; Dekker, 2011). Following the work of Perrow, there have been various approaches to describe and understand complexity, as well as many different definitions of complexity. However, any attempts to quantify complexity and relate it to the safety performance of systems have not yet lead to conclusive results.

Eurocontrol (2004) performed an extensive literature study on the topic of Cognitive Complexity of Air Traffic Control, followed by a report with the title "Complexity Metrics for ANSP Benchmarking analysis" (Eurocontrol, 2006), in which air traffic complexity is numerically used as a basis for benchmarking ATC recruitment. Based on the work of Eurocontrol, several efforts have been taken to apply the metric and relate it to safety. Djokic (2009) detailed out the Eurocontrol metric, calculated complexity for a large number of actual air traffic situations and tried to correlate it with the calculated probability of loss of separation, without finding any significant associations. Kristic Simic (2010) described the operational simulation of aircraft landing at and departing from two different airport configurations and the evolution over time of the complexity, as calculated by a derivative of the Eurocontrol metric, with the purpose of giving controllers an insight in their expected workload. Diaconu (2014) used the Eurocontrol metric to determine over time the evolution of the air traffic complexity in the Bucharest Air Control Center in order to validate the actually required staffing.

From System Complexity (SC) we proceed to the complexity of the system as perceived by the individual(s) responsible for controlling the system, the so-called Perceived System Complexity ($SC_{perceived}$). The performance of the human controller was discussed by Eurocontrol (2004)

in their literature survey as a mediating factor to be applied onto System Complexity alias Taskload to arrive at Mental Workload, as perceived by the operator in control. Schöttl (2015) applied a metric called "Perception", reflecting the mental state of the person that is assigned with the duty to control the system. In Schöttl's approach, Perception is linked to mental fitness and experience of the operator, separately graded and combined in one score between 1 and 10. In this paper we use System Complexity in combination with the metric Human Performance according to the Contextual Control Model as published by Hollnagel in 1993 (Hollnagel, 2017), specifying four different levels of control reaction to external disturbances, being the random, opportunistic, tactical and strategic control level of the intervening operator. Finally, we link the dynamic Relative Perceived System Complexity to the occurrence of incidents.

2　　System Definition

A system is defined by the Federal Aviation Administration (2000) as 'A composite of people, procedures, materials, tools, equipment, facilities, and software operating in a specific environment to perform a specific task or achieve a specific purpose, support, or mission requirement'. For the scope of this paper we followed the principles of general systems engineering by assuming that each system is characterized by (1) the main process(es) under concern through which (2) input(s) are transformed into (3) output(s) using (4) resources and (5) incorporating controls for specific levels of disturbances. The type and extent to which disturbances are considered, depending on the system boundaries as defined by the analyst: disturbances originating inside the system or at the system borders.

For the scope of the complexity metric, the processes are defined as the highest-level processes each user performs to generate the desired system deliverables. For example in the aviation sector:

- The process of flying an aircraft is a high-level process that can be decomposed into lower-level processes (i.e. control, navigate, communicate etc.), which in turn can be further decomposed depending on the scope of the analysis. Thus, from a pilot's perspective, the processes of controlling, navigating and communicating might be considered as the main high-level processes. The system elements with which the flight crew interacts are other aircraft, Air Traffic Control, all devices that provide information (or cause distraction!) to the pilot and the different means that assist the pilots in controlling the aircraft (e.g., engine

throttles, stick). The interactions may be physical (e.g. advancing the throttle) or informative (e.g. acquisition of ATC-instructions).

- From the perspective of air traffic management of given airspace, the air traffic process of all individual aircraft in this airspace is the highest-level process to be considered, the flight of each aircraft within the airspace is the next lower level of processes. The different aircraft are the elements which constitute the system in combination with the technical systems enabling the task of control (e.g., radars, displays, communications) and other human controllers which assist in the activities of air traffic control (e.g., shift supervisor, weather information services).

- Regarding ground handling teams, the turnaround process is the main high-level process, with subprocesses like fuel supply, baggage transport and loading, catering, cleaning etc. All parties executing their individual subprocess in parallel are the elements of the system. Interactions can be physical, functional and/or communicative as well. As long as every individual element remains in its allocated subspace, no physical interactions between the servicing elements will occur. However, there are various interdependencies, trivial as well as hidden. The cleaning activities can only start when debarkation of the passengers is finished, but the debarkation of passengers from the plane also has direct interaction with the unloading of the baggage (e.g., unbalance may cause the plane to tip over)

- In the field of technical support, maintenance is the process under review, with all supporting activities as subprocesses. The system elements are all persons acting or interacting with each other in physical, functional or communicative ways as well as the equipment used.

3   System Complexity metric

For Eurocontrol, when dealing with aircraft in airspace that has to be kept separated from one another, complexity only exists when aircraft headings are not the same, or vertical climb rates differ or when speeds differ (Eurocontrol, 2006). In short: when aircraft trajectories might cross, complexity increases and may give rise to a need for intervention by a controller. Therefore, for an operator, tasked to keep the aircraft in given airspace separated from one another, the complexity of a given space cell during a given time frame is:

$$SC = \sum_{i=1}^{NE} \sum_{j=1}^{NI_i} (DI_{ij} * w_{ij})$$

(1)

where:

- NE is the total number of elements present in that cell space.
- DI_{ij} represents the degree of interaction between element i and element j and takes the value of 0 in case of no interaction between two elements, or the values 1, 2 or 3 depending on the existence of a single, double or triple interaction between two elements correspondingly.
- NI_i is the total number of elements, interacting with element i.
- w_{ij} is a weighing factor equal to the fraction of the flying time in the cell that the interaction between element i and j existed.

In the case of objects physically moving through space, the existence of an interaction DI in Formula 1 means that the distance *is changing d_{ij}* between two elements i and j. Hence, in this case we can write the system complexity on a given moment in time as:

$$SC(t) = \sum_{i=1}^{NE} \sum_{j=1}^{NI_i} \left(\frac{-\dot{d}_{ij}}{d_{ij}} \right) \qquad (2a)$$

where $\dot{d}_{ij}$ is the change of the distance between elements i and j per second.

This expression shows that when a direct interaction DI is written as $-\dot{d}_{ij}/d_{ij}$, it equals to $1/T_{window}$, T_{window} being the time period in which an operator shall prevent clash (or a distance smaller than acceptable) between elements i and j. The shorter the T_{window} becomes, the higher the system complexity will be. Formula (2a) can be written accordingly as:

$$SC(t) = \sum_{i=1}^{NE} \sum_{j=1}^{NI_i} \left(\frac{1}{T_{window\ ij}} \right) \qquad (2b)$$

T_{window} can be compared with the time window Hollnagel (2017) presents in his Contextual Control Model (COCOM) for the consecutively understanding, planning and acting upon the occurrence of the unexpected event.

Another important element in the complexity metric are the factors that play a role in controlling the process. Besides Human Resources (HR), system control is not possible without adequate Technical Resources (TR). Also, Communication and Anticipation (CA) portrayes a decisive role in controlling complex systems (Sharpinskykh, 2017). Communication represents all effective functional exchange of information between the controller and the elements and between the elements themselves. Anticipation

covers the cognitive capability of the elements to react in advance, on the basis of their experience and knowledge. For this paper, we combine these three factors in the term Slack (SL), through the generic expression SL = [HR, TR, CA]. In general, one can state that if distances between elements become smaller or are decreasing at a higher rate, more and more sophisticated tools are needed to stay in control as well as communication and anticipation become increasingly crucial to prevent incidents from happening. Therefore, system complexity is expressed as:

$$SC(t) = \left[\sum_{i=1}^{NE}\sum_{j=1}^{NI_i}\left(\frac{-\dot{d}_{ij}}{d_{ij}}\right)\right] * \frac{1}{SL} \tag{3}$$

The sums in Formula 3 represent the system to be controlled and the SL parameter reflects the resources available to control it, and combined together in $SC(t)$ they represent the difficulty of the control task.

4   Task difficulty, task load and workload

Any difficult task may be feasible as long as the user is adequately experienced in controlling the corresponding situations, mentally and physically fit, and able to use the available tools effectively. Adverse events might occur because the operator is tired, does not understand the situation or is subject to other factors influencing the human ability to control a situation. Therefore, in line with Eurocontrol (2004) and Schöttl (2015), we multiply the system complexity SC by Human Performance (HP), a factor representing all elements that might limit human performance, and we conclude to the perceived system complexity SC$_{perceived}$:

$$SC_{perceived} = SC * HP = \left[\sum_{i=1}^{NE}\sum_{j=1}^{NI_i}\left(\frac{-\dot{d}_{ij}}{d_{ij}}\right)\right] * \frac{1}{SL} * HP \tag{4}$$

For HP we choose an integer, ranging from 1-4, representing the four control modes as defined by Hollnagel (2017), being 4=scrambled or random control mode, where the operator has no idea what to do and acts impulsively, 3=opportunistic mode, 2=tactical mode and 1=strategic control mode, in which the controller handles the system complexity in a long-term stable way. It is clear that training controllers for exceptional situations to follow emergency procedures results

in keeping HP on a low value, and thus limiting the sudden increase of perceived complexity.

5   Minimizing complexity

Based on the complexity formula above (Formula 4), it is interesting to determine the conditions for lowest possible SC, as this situation requires the lowest level of control measures. It is evident that ample slack lowers system complexity: sufficient staff, technologically advanced tools and trained procedures. But complexity actually becomes minimal when there are no interactions DI. This situation represents a system state which requires the least effort to control it and is therefore preferable if circumstances allow. For the case of an air space controller, minimizing complexity means that all aircraft in the space cell under consideration have the same heading, the same climb rate and the same speed, as that makes $\dot{d}_{ij}$ zero within the space cell in formula 4. One can take this one step further and define the requirements for space cells such that complexity is minimized:

- Space cells shall have one type of (air)traffic, all moving (flying) at the same speed, with the same heading and the same climb rate, from one entry point at one side of the space cell all the way to one exit point at the other end of the space cell.
- One controlling authority shall monitor all traffic in one space cell to ensure that flight crews follow the rules and stick to the planned route. In other words, the controller shall check whether complexity remains "zero" and take appropriate actions to null complexity again in case it should increase unintendedly.

Regarding the land traffic, it is also organised this way with separate non-intersecting lanes for pedestrians, bicycles and cars, with all vehicles moving within a lane at similar speeds and similar headings. If intersections cannot be avoided controls shall be in place or speeds shall be strongly reduced in order to create a time window that allows the human mind to prepare and execute a well-thought-out action. In case high-speed crossings are inevitable, crossings shall occur by a slow merging of parallel lanes, thus minimising the differences in speed of the elements, like the design of our motorways.

Another example of minimising complexity can be found at the ground services during a turnaround process of an aircraft on the apron, where "zero" complexity means that:

- While the aircraft is taxiing to its gate position the entire space, through which the aircraft is moving, is allocated to the aircraft alone, up to the moment it halts, and the engines are shut down. No other elements are allowed within this space.
- After the aircraft comes to a halt, the space around the aircraft shall be handed over to ground service operations, of which all individual elements (task groups) have their own subspace allocated to them to perform their individual tasks in parallel.
- Upon completion of the individual turnaround tasks, the complete area around the aircraft shall be handed over to the aircraft again by a central controller, and the aircraft will be allowed to move again through its allocated space

We can also follow the same approach to minimise the complexity of an (aircraft) maintenance task. In this case, minimising complexity means that:

- Every maintenance technician uses his/her own tools
- Every maintenance technician performs one task within a given timeframe (series work mode)
- There are no more than one maintenance technician working at the same time on the subsystem for accomplishing different tasks
- Communication is minimised to the extent necessary for coordinating the activities performed between the technicians involved

Minimal complexity for the controller also means removing all devices which may provide him with non-relevant information and rather distract the controller than support him in his most important control task. A clear example is the removal of large billboards from the direct neighbourhood of a pedestrian crossing in London when incident rates increased after distracting advertisements were revealed. Minimizing complexity for the driver of a car also means eliminating distracting devices from inside the car, unless of course the control of the car is automated and made independent from the activities of the "driver".

6   Increased Complexity

Taking Formula 4, it can be concluded that three following factors can lead to a rise in complexity:

A. increase in DI's
B. a decrease in Slack
C. a decrease in Human Performance

Factor C covers a wide variety of situations where controllers are unable to control their system. One can think of physical or mental health issues affecting the adequate functioning of the pilot. Also, extraordinary circumstances, possibly as a consequence of technical anomalies, for which the pilots are not trained, can cause so much stress that the logical solution to control the system in a non-standard situation will not be found by the controller within the time available.

Factor B represents sudden shortages of resources such as inadequate amount of fuel, decreased the technical performance of the system or insufficient human resources to accomplish a task within defined time limits and according to standards.

Factor A is connected with the question: what changes can cause the DI's to increase sharply? Mathematically a sensitivity analysis can be performed for $\dfrac{\partial SC}{\partial x}$ where x are the relevant variables that determine interactions. When considering a number of aircraft flying the same headings, climb rates and speeds, Formula 2 results in zero complexity. However, if one of the aircraft changes heading and/or climb rate and/or speed, a lot of DI's might be created. This, though, will not be a real problem as long as there is a lot of space between the interacting elements to react in time and properly.

As an example let us consider the case where birdwatchers at an airport are allowed to access the runway instead of moving on their own paveway alongside the runway. In this case, two different types of elements, cars and aeroplanes on final, are moving through the same subspace at significantly differing speeds, even without the birdwatcher hearing the communication with the plane on final, and, even worse, each under a different control authority. This alone is already a threefold violation of the requirements for minimal complexity. A delay of the birdwatcher in evacuating the runway when a plane is on final will lead to a significant reduction in the time window for the aircraft to land safely, thus being forced to perform a go-around. But this go-around, taking into account an airport configuration with crossing runways, will generate a completely new set of unplanned DI's when aircraft are taking off from the crossing runway. Even this should not have to be a problem: as long as the air traffic controllers are trained for this exceptional situation, their HP factor will be 2 or 1 and the dynamic increase in System complexity will be limited.

7 Complexity in relation to safety: our hypothesis

The complexity of a system is not perse linked to safety. Complexity only determines the number of measures needed to control the system: the higher the complexity of a system rises, the more advanced technical and human resources and the more communication and anticipation are needed to control it. In our hypothesis safety is at stake when unplanned interactions arise, temporarily increasing the system complexity in an unplanned way, a situation we did not foresee when planning the nominal control measures. Our hypothesis is that the higher the score of Relative Perceived Complexity RPC=[(SC_{actual} / $SC_{designed}$) * HP_{actual}/ $HP_{designed}$] the more the non-safety outcomes will be, when controlling the system towards the objectives (e.g. in terms of quality, productivity, efficiency). The term "designed" or "planned" system complexity refers in principle to the system as described in the respective manuals, procedures etc. Stated differently: for safety, we focus on the deviation of the actual dynamic system complexity ("Work-as-Done") from the static, planned system complexity ("Work-as-Imagined"). Our hypothesis is that their ratio will be related to safety outcomes, as shown mathematically in Formula 5 below.

$$\text{Safety outcome:} \frac{SC_{perceived\,actual}}{SC_{perceived\,designed}} = \frac{SC_{actual}}{SC_{designed}} * \frac{HP_{actual}}{HP_{designed}} =$$

$$= \frac{\left[\left|\sum_{i=1}^{NE_a}\sum_{j=1}^{NI_i a}\left(\frac{-\dot{d}_{ij}}{d_{ij}}\right)\right|_{actual}\right]\Big/ SL_{actual}}{\left[\left|\sum_{i=1}^{NE_e}\sum_{j=1}^{NI_i e}\left(\frac{-\dot{d}_{ij}}{d_{ij}}\right)\right|_{designed} * w_{ij,designed}\right]\Big/ SL_{designed}} * \frac{HP_{actual}}{HP_{designed}} \tag{5}$$

In this expression the values of $SL_{designed}$ and $HP_{designed}$ could be set to "1", representing nominal situations. The time-dependent information about positions of the system elements, d_{ij}-actual, will allow performing the rest of the calculations.

8 Conclusion

In this report we have first defined complexity as a metric, consisting of the total of the direct interactions between all system elements themselves in combination with the factors that support the controller in his control task, like communication and anticipation and technical and human resources. Then we added the human performance metric HP to arrive at the system

complexity as perceived by the operator: $SC_{perceived}$. Finally, we postulated that not complexity is linked to safety but that the unplanned, dynamic increases in perceived complexity are linked to safety via the relative perceived complexity RPC.

As a consequence, preventing circumstances, that might lead to a dynamic increase of SC, as well as intensive training of controllers to handle the consequences of these unforeseen circumstances (minimizing HP_{actual}) are the ways to maintain safety.

In order to validate this hypothetical relation, in the next phase of the project, we plan to study in a structured way a wide variety of systems, all with moving elements, all in different circumstances, for which the system complexities will be assessed and correlated with the occurrence of incidents.

Acknowledgments

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