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Modelling the human components of complex systems

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Complex systems are specified, designed, built and tested by humans, all of whom are immersed in a cultural environment that colours their emotions, cognition, decisions and behaviours. This paper presents a brief overview of culture, its sources, its measurement and its effects on the performance of complex systems. This paper also describes a series of culture and personality modelling tools that the authors have developed for the purpose of assessing the match of individuals and teams to missions or tasks, based on their cultural backgrounds and/or personality traits.

Index Terms— **complex systems, cultural dimensions, ethnic culture, multicultural teams, personality traits**

I. Introduction

As technical systems have become more complex, systems modelling tools have advanced in capability; some tools now offer the facility to model systems from many viewpoints, and to integrate those viewpoints. SysML is the latest and, potentially, the most useful in a long line of systems modelling tools.

In contrast to our advanced abilities to model complex technical systems, our abilities to model the behaviours of complex system users, beyond treating them as logical units, is very limited. Transport and military aircraft, air traffic control systems and power stations are sold across the World by international or global companies. Such systems typically embody the unconscious assumptions of their designers, that the users will have the same general attitudes, ways of thinking and behaviours that they have, i.e. that designer and user share the same culture; evidence for this is presented in Section IV of this paper. The designer is a key component of the design system, and the user is a key component of the designed system; therefore we need to model (or at least take account of) both of them if we are to achieve predictable performance in both our systems engineering processes and systems-engineered products and services.

Although there are many mature human factor tools that can model human *capabilities*, they cannot reliably model human *behaviours* under specific circumstances.

II. Human culture

At the level of the social group or society, the term 'culture' relates to a set of values, assumptions, preferences, beliefs, rituals and behaviours. These have evolved over multiple generations to be commonly-held, and have (usually) improved that group's fit with the environment, thereby increasing its survivability. At the level of the individual, the acquisition of this 'culture' brings the same benefits. In addition, the acquisition of this common culture, identifies individuals as members of the group, and thereby protects them to some extent from other members of the group.

The genetically-endowed ability of humans (and to a lesser extent that of other primates) to acquire post-birth updates to their 'firmware' has provided advantages in terms of adaptation; culture can change much more rapidly in response to environmental changes than can the underlying genetically-defined 'hard wiring'. However, because culture is acquired largely unconsciously, most people are not fully aware of their own culture; it is only when they find themselves amongst people of another culture and experience 'culture clash' that they perhaps examine their own culture.

A definition of culture

Following a survey of culture-related research, including the work of Tylor [1], Goodenough [2], Levine [3], Triandis [4], Barnard [5], Kubr [6] and Hofstede [7], the authors have defined culture as:

> *" … an unconsciously acquired, shared set of values, preferences, attitudes, beliefs and rules that influence individual and group emotions, and their behaviours towards individuals, groups, the environment and other artefacts."*

As stated earlier, a key factor of culture is its unconscious acquisition and the individual's resultant lack of awareness of his or her own culture. A further key factor is that culture is a group-based phenomenon; as stated by De Waal and Bonnie [8], "the culture label does not apply to knowledge, habits or skills that individuals can and will readily acquire on their own."

Sources of culture

The following sources (or forms) of culture are amongst the most widely recognized in the literature – ethnic (or national) culture, organizational culture and professional culture. An excellent account of the effects of these three forms of culture is provided in Helmreich and Merritt's book on culture in aviation and medicine [9].

1) Ethnic (or national) culture

In many countries, there are two or more religious or racial groups; in such cases, national culture may not be synonymous with ethnic culture. However, such ethnic cultures are in most cases overlaid with common elements of national culture due to shared communication media, education, etc. In addition, most data available from sources such as the United Nations and the European Commission are based on

nationalities, rather than ethnicities. Therefore, for the purposes of this paper, ethnic culture and national culture are assumed to have the same meaning unless otherwise specified.

Ethnic culture arises from factors such as heritage, religion, history, language, climate, population density, availability of resources, and politics. Acquisition of ethnic culture starts at a very early age; therefore, once acquired, it is resistant to change. There are significant differences in attitudes and behaviours between people of different ethnic cultures; these differences affect areas such as superior/inferior relationships, leadership styles, communication styles, trust, and attitudes to rules, uncertainty, time, trust, honour and losing face.

2) Organizational culture

The culture of an organization is a product of its history, leadership, products and services, etc. In the case of a multi-national or global company, there is typically a common layer at the top of the organization; however, there are differences underneath that common layer due to differing ethnic cultures, e.g. in leadership styles and manager-subordinate relationships. Organizations have formal hierarchies and rules, therefore organizational culture is more amenable to carefully-planned change than are either ethnic or professional cultures. Changes imposed by the distant head office that run counter to local ethnic culture will trigger antagonism and resistance, whereas changes that are aligned to ethnic culture can bring performance improvements. Factors that encourage a positive organizational culture include strong corporate identity, effective leadership, empowerment, job security, cohesive team-working, high morale and trust.

3) Professional culture

Engineers, scientists, teachers, accountants, physicians, airline pilots and many others possess highly specific professional cultures that overlay their ethnic or national cultures. Professional cultures typically include features such as selection for entry to the profession, profession-specific expertise and jargon, status and uniform, stereotyping, self-regulation, resistance to change and reduced awareness of personal limitations.

Individuals acquire their professional cultures later than they acquire their ethnic cultures. As a result, when faced with conflicting behavioural inclinations from the two cultures, particularly in threat situations, the earlier-acquired ethnic culture may rise to the fore. Therefore, critical elements of professional culture (e.g. relating to safety) need to be instilled by extensive training, and reinforced by regular retraining and practice.

Individual and team cultures

1) Individual culture

Individuals are moulded by their exposures to the above three cultural sources (ethnic, organizational and professional), and also by their genetic predispositions and unique experiences. Therefore, although individuals will reflect particular cultures in terms of general attitudes, preferences and aversions, they will not be clones of those cultures.

2) Team or group culture

Teams are widely employed in companies in order to solve specific problems and to develop new products or services. Team effectiveness is therefore very relevant to systems engineering activities; team effectiveness is also relevant to the performance of many of the complex products of systems engineering.

Western companies began to use multicultural work teams increasingly widely during the 1980s. At this time, the effects of multiple cultures on team performance were not well understood and early experiences of multinational and multi-cultural teams were disappointing. Managers found the development and utilisation of multicultural teams to be fraught with problems [10] and the level of performance to be low [11]; difficulties were often experienced when attempting to integrate team members into cohesive, functional teams. However, where effective integration has been achieved within multicultural teams, they have often performed better in terms of decision-making than homogenous (single-culture) teams, particularly in situations where the development of a large number of alternative ideas has been important to the achievement of a good solution [12], [13], [14].

It is clear from industrial experiences with multicultural teams to-date that interactions between individuals of different cultures are more complex than those between individuals that share the same or a similar culture; team members cannot rely on informal processes to come into play to enable a team ethos to form. Supporting evidence for this comes from a two year study by Snow et al. [15] of multicultural teams at thirteen companies. From the data collected on these teams and their performances, Snow et al. concluded that preconditions for multicultural team effectiveness include the development of clear processes for communicating, decision-making and handling conflicts and disagreements.

Team member cultures, team size, team leadership, team longevity, task types and the level of external control all affect the level of cohesiveness, the potential emergent hybrid culture, the degree of social loafing and the perceived team efficacy; these factors, in turn, influence the overall team performance. The formation of a team hybrid culture is particularly important because, without it, the team may fragment into culture-based subgroups that compete rather than collaborate.

Although there are several limited descriptive models of multicultural teams, for example that of Earley & Gibson [16], little guidance is available for would-be multicultural team leaders other than checklists and historical accounts of team successes and failures in the field.

The research described in this paper is concerned primarily with teams formed from multiple ethnic cultures, but it is worth noting that similar problems can also arise in teams containing multiple professional or organizational cultures. A systems engineering team consisting of engineers, architects and managers may find that differences relating to jargon and attitudes to risk and time cause problems. A team drawn from members of a large corporation and members of a small, agile company may find that issues relating to trust, formality and status interfere with productive discussions and planning.

III. The Measurement of Culture

In order to predict the performance of individuals, groups and systems on the basis of their cultures, relevant cultural 'yardsticks' are required. These cultural factors, attributes or

dimensions (as they are called) are typically described in terms of a scale between two extremes. By scoring individuals and societies on the scales of a set of cultural dimensions, they can be placed in the 'multi-dimensional culture space', and compared to other individuals and societies.

Over the last half century, researchers in human culture have produced various sets of cultural dimensions that appear to capture differences between people of various communities. Between 1967 and 1973, Hofstede [7] carried out a major study of the cultural traits of IBM employees across subsidiaries in forty countries. Based on the results, he proposed a four-dimension cultural framework consisting of individualism (vs. collectivism), power distance, masculinity (vs. femininity) and uncertainty avoidance; see Table I for the meanings of these dimensions. This framework has been revalidated many times in later studies, for example see [17], [18] and [19]. Following work by Chinese researchers, Hofstede added a fifth dimension – long term orientation [20].

Table I: Hofstede's original four cultural dimensions

Cultural dimension	**Description of extreme values**	
Individualism vs. collectivism (IDV)	**Individualism:** Ties between individuals (other than immediate family members) tend to be loose; individualists take personal responsibility for their actions, typically speak directly and factually, and are willing to argue and to question others' views.	**Collectivism:** Individuals are integrated into closely knit groups; in return for unquestioning loyalty, they gain the protection of their group. They try to avoid direct, confrontational approaches. Hierarchies are rigid, and losing face is to be avoided at all costs.
Power distance (PDI)	**Low power distance:** Decisions are more likely to be made by agents with appropriate knowledge and experience, irrespective of roles.	**High power distance:** Decisions are made by those in authority, dispatched downwards, rarely questioned, never overridden.
Masculinity vs. femininity (MAS)	**Masculinity:** Challenge and recognition are important. There are significant role differences between the genders.	**Femininity:** Co-operation and relationships are important. Society minimizes gender role differences and inequality.
Uncertainty avoidance (UAI)	**Low uncertainty avoidance:** Members of such cultures have a high tolerance for uncertainty and ambiguity.	**High uncertainty avoidance:** Such cultures will seek to reduce uncertainty, e.g. via laws, rules.

One of the largest recent studies of culture, the GLOBE Study [21], examined the attitudes and beliefs of more than 17,000 managers in 62 countries. The GLOBE Study was later extended to produce a more in-depth study of 25 societies [22]. The GLOBE cultural framework consists of nine cultural dimensions, including several that are similar or equivalent to Hofstede's dimensions.

Although there is as yet no universally-agreed set of cultural dimensions, certain dimensions (and minor variations on them) have been found to be statistically robust in their application, in particular Hofstede's cultural dimensions.

IV. Cultural Issues and Effects

The development of systems engineering practice has been led largely by Anglo and North European engineers (the term 'Anglo' refers to ethnic groups of British descent, for example Canadians, Americans, Australians and New Zealanders). As a result, systems engineering methods and standards tend to reflect these *individualistic*, low *power distance*, low *uncertainty avoidance* cultures.

As stated in the introduction, if engineers are not consciously aware of cultural differences, their unconscious assumptions when designing complex systems will be that system users share their culture. These systems will therefore exhibit certain cultural traits, or will require certain cultural traits in their human components (users), in order to work optimally. User culture influences the ways that users of complex systems communicate with each other and respond to situations and events. It is therefore important to recognize such influences when designing systems. In operation, complex systems include physical/software systems, operating and reporting procedures, training procedures and facilities, and the users. In the case of aircraft systems, all of these system components, other than the user, may reflect Anglo/North European values. Examples of issues arising from this are discussed briefly in the following subsections.

Accident rates in NATO air forces

An investigation into the accident rates of fourteen NATO air forces between 1988 and 1995 was carried out by Soeters and Boer [23]. These air forces had similar or identical aircraft fleets, similar training procedures, and had operating procedures that had been harmonized across air forces; in addition, they were involved in regular exchanges of personnel with other NATO air forces and also took part in regular combined exercises with other NATO countries. As a result, there were similar professional and organizational cultures across these NATO air forces. Nevertheless, there were wide variations in accident rates, which were strongly, positively correlated to three national culture dimensions – *high* collectivism, *high* power distance and *high* uncertainty avoidance. Despite the common professional organizational and professional cultures, the underlying national (or ethnic) cultures exerted an influence on crew behaviours at critical junctures.

Most NATO regulations, operating procedures and training regimes are based on the US/British model, with its assumptions of *low* collectivism, *low* power distance and *low* uncertainty avoidance.

Accident rates in commercial aviation

An investigation into airline accident rates during the 1980's and 1990's by Jing et al. [24] revealed that the cultural dimension of authoritarianism (similar to power distance) was positively correlated to accident rates and accounted for more than half the difference in accident rates between cultures. Authoritarianism is very high in China, Taiwan and South Korea, which had some of the worst accident rates in the World during the period covered by the investigation. Black box and voice recorder evidence revealed how communication problems between authoritarian crew members led to failures to react promptly in critical situations.

As is the case with NATO air forces, most commercial aircraft, their operating procedures and training processes are designed by and for US and Northern European cultures.

Culture-sensitive designs

Clearly, authoritarian (or high power distance) cultures impose barriers to prompt, effective, factual communication amongst crew or team members, thus reducing the efficiency of such crews or teams in situations that require swift coordinated responses. However, culture-sensitive designs that include (for example) the earlier intervention of automated aural warnings and alarms could at least mitigate the effects of this communication problem.

V. A CULTURAL TOOL – THE SFMT

The authors were initially tasked to carry out research into the effects of culture on military systems and missions. This work was supported by the UK's Ministry of Defence via its Systems Engineering and Integrated Systems for Defence: Autonomous and Semi-Autonomous Vehicles Defence Technology Centre (SEAS-DTC).

Table II: The SFMT nine cultural dimensions

Cultural dimension	Description of extreme values	
Degree of collectivism	**Low (individualistic):** Similar to Hofstede's description.	**High:** Similar to Hofstede's description.
Universalism vs. particularism	**Universalism:** Consistent treatment of others, application of rules is not dependent on the person or organization.	**Particularism:** Rules and laws vary in their application dependent on the person or organization.
Masculinity	**Masculinity:** Similar to Hofstede's description.	**Femininity:** Similar to Hofstede's description.
Basis of power	**Power by achievement:** Individuals are promoted on the basis of personal performance and success; reduces nepotism.	**Power by status:** Individuals are promoted on the basis of seniority and (long) experience.
Mastery vs. fatalism	**Mastery:** One can always overcome obstacles by directed effort; individuals are willing to plan long term.	**Fatalism:** Everything is predordained, and detailed planning is pointless – better to react to whatever turns up.
Rule flexibility	**Proactive:** Local characteristics can lead to exceptions or modified rules or procedures. Appropriate for special forces.	**Orthodox:** Broad or generalized rules are mandatory, you must just find the best fit. Useful for large operations that need cohesion.
Time management	**Time synchronization:** Synchronizing across tasks and units, co-ordination rather than detailed time scheduling, shifting timescales as necessary.	**Time sequencing:** Predefined ordering of events, tasks should be completed ASAP; efficiency and timeliness are important.
Power distance	**Low:** Similar to Hofstede's description.	**High:** Similar to Hofstede's description.
Attitude to risk	**Low risk-taking:** A respect for and acceptance of doctrine, strategies and standard operational procedures; a great concern for consequences.	**High risk-taking:** An acceptance of the unpredictable; able to react to chaotic events; a willingness to break the rules and accept the consequences.

Based on the above research, a culture tool was developed - the Soft Factors Modelling Tool (SFMT). This tool enables the user to define a mission environment and the desirable 'agent' behavioural capabilities by selecting and scoring options listed in tables. Then, the cultural dimension scores of agents (individuals and/or groups) selected for the mission can be entered; a series of 'dilemmas' are provided to assist in this activity. On completing the inputs, the tool calculates deviances from ideal cultural scores for the various facets of the environment and desirable behaviours. The results are presented as detailed and summary mismatch scores; a 'traffic light' colour scheme is also used in order to draw attention to the most problematic areas.

The SFMT utilizes a set of nine cultural dimensions, based on factors that are perceived as important in UK and US military literature, see Table II. The SFMT environment and behaviour tables also reflect the military environment.

The SFMT has been evaluated using case studies of military activities in Bosnia, Sierra Leone, the Gulf and Afghanistan; these were based on well-documented historical military operations and events for which the cultural traits of individuals or groups could be determined with a reasonable level of accuracy. The tool indicated problem areas that were broadly in accordance with those identified in the historical documentation. However, when the tool was used for civilian situations (e.g. to investigate issues that were occurring in a medium-sized design company), it was found to be more difficult to use because the military mission environment options did not fit well with civilian situations, and the militarily-biased cultural dimensions were less than ideal. More details of the original SFMT tool can be found in [25].

VI. THE INTRODUCTION OF PERSONALITY TRAITS

The author's research group has changed the emphasis of future soft factors research from the military environment to the industrial and commercial environments. In particular, it is now researching the issues that arise in multicultural work teams (MCWTs).

There is a considerable body of work on single-culture work teams including the processes they go through – for example Tuckman's five stages of group development [26], and the roles in the work team – for example Belbin's nine team roles [27]. Team role theories identify different types of people for different roles, i.e. different personalities.

Table III: The FFM personality dimensions

'Big Five' dimensions	Opposing dimension values	
Surgency	**Introversion:** More interested in the ideas and concepts that form the inner world.	**Extraversion:** Having a keen interest in other people and external events.
Agreeableness	**Hostility:** Suspicious and uncooperative.	**Friendliness:** Trusting and helpful.
Conscientiousness	**Low:** Lazy and careless.	**High:** Hard-working and reliable.
Neuroticism	**Low:** Having high stability and low anxiety.	**High:** Having low stability, high levels of anxiety and high volatility.
Intellect (openness)	**Low:** Conventional and down-to-earth.	**High:** Nonconformist and creative.

There is evidence from the research literature and industrial practice that personality plays a significant a part in the way teams perform; in particular, diversity in personality types is necessary for effective performance [28]. Furthermore, recent research has indicated that culture and personality are not independent of each other [29]. In addition, a number of controversies have arisen over the use of cultural dimension scores at the level of the individual, in part because culture is ultimately a group phenomenon; Hofstede describes this issue as the *ecological fallacy* [20], p16. A decision has therefore

been made to develop the SFMT to include personality dimensions. Based on overwhelming evidence of its stability across time and cultures, for examples see [30], [31], [32], the Five Factor Model of personality (FFM) was chosen. Table III lists the FFM personality dimensions.

VII. Two Revised Cultural Tools

The changed requirements described in Section VI have resulted in two revised versions of the Soft Factors Modelling Tool, the SFMT2 and SFMT3.

The SFMT2

This tool includes two major changes from the original SFMT. The first change relates to the inclusion of a reduced set of cultural dimensions, now consisting of the original four cultural dimensions used by Hofstede. These were selected because, as stated earlier, they appear to have been validated and utilised more than others, and also because three out of four of them have a high statistically-verified effect on human performance. The second change relates to the inclusion of the five personality dimension framework of the FFM. These changes result in a total of nine dimensions for the SFMT2 – four cultural dimensions (see Table I) plus five personality dimensions (see Table III).

The SFMT2 (see Figure 1) has retained the military mission environment of the original SFMT in order to enable comparisons to be made between it and the original SFMT using similar historical mission information. These comparisons have proved to be difficult to achieve, as much less personality-related information has been available in the case study material than culture-related information. However, these comparative evaluations have revealed several interesting differences between the cultural dimensions and two of the personality dimensions. Whereas an individual may have a cultural trait that does not fit well with certain aspects of a mission, that trait may fit well with other aspects of the mission, and may fit with a different mission very well. However, personality traits such as high neuroticism and low conscientiousness (laziness, carelessness) are unlikely to bring many benefits to any mission or task, and score badly in all critical areas – this proved to be the case when the comparative evaluations between the SFMT and SFMT2 that were carried out.

The SFMT3

The SFMT3 addresses a limitation of the original SFMT tool that is not addressed by the SFMT2; this relates to the issues associated with the military environment and its limited applicability in a commercial or industrial environment. To this end, the environment has been changed to some degree to be more sympathetic to a generic industrial/commercial task/-problem environment. As with the SFMT and SFMT2, a specific environment can be defined quickly and easily by selecting and scoring a number of options. Note that this change still requires detailed validation.

The SFMT3 provides additional quantitative information compared to earlier tools, in particular, values for mean and maximum cultural diversity in the group or team, based on cultural distances between team members. This information is important, as it is a guide to the likelihood of problems of communication, particularly in a new team, and is also a predictor of potential team fragmentation. Preliminary evaluation of this feature as a predictor of fragmentation is awaiting a study of student teams in the university where the researchers work.

The SFMT3 also provides values for mean and maximum personality trait distances between team members. However, this feature is not currently utilised in further assessments of team efficacy because, although diverse personality traits are considered valuable in order to fill team roles [28], diversity along either the conscientiousness or neuroticism axes is unlikely to provide benefits.

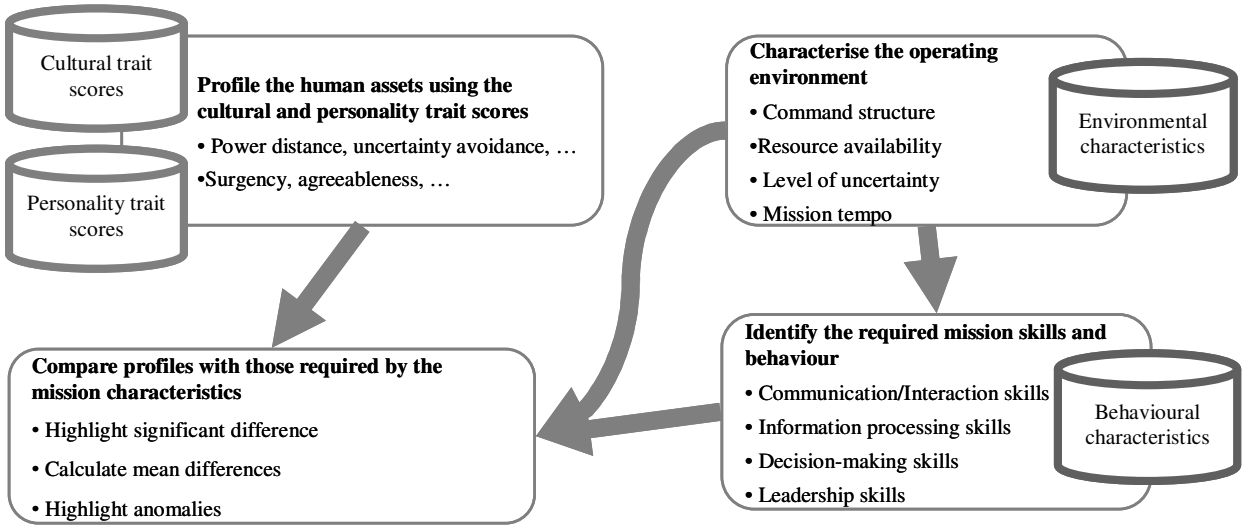

Fig. 1. Simple flow diagram of the SFMT2

VIII. Discussion

As high technology systems improve in terms of performance and reliability, the performance limitations of the human elements of such systems are increasingly exposed. It is important, therefore, to model these human elements – not

only in terms of what they *can do*, but in terms of what they *are likely to do* in various situations.

The nations that individuals grow up in, the organizations they join and the professional careers they pursue, all contribute to these individuals' cultural traits. In turn, these cultural traits affect the way that individuals and members of teams see the world, communicate with each other and interact with complex technical systems. Most commercial and military aircraft are designed by Anglo and North European engineers, as are their standard operating procedures. Accident rates for these aircraft are positively correlated to the cultural differences between these engineers and the aircraft crews.

The authors of this paper have developed several tools that model culture. These 'Soft Factor Modelling Tools' (SFMT, SFMT2 and SFMT3) are intended to provide estimates of the goodness of fit of individuals and teams to missions or tasks. These estimates are based on cultural traits in the case of the SFMT, and on cultural and personality traits in the case of the SFMT2 & SFMT3. The original SFMT has been evaluated via a wide variety of case studies; the later tools have only been partially evaluated.

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