Measurement systems are as old as the advent of agricultural civilizations and as diverse as the multitude of cultures. They merged during history and began to pose seriously increasing conversion problems during the last century with the advent of industrialization and, especially, the rise of the global village. The most serious and negative impacts of using different (e.g., metric vs. imperial) measurement systems in complex mission and safety-critical systems engineering (e.g., transport, energy, etc.) and engineering in general are accidents/incidents/near misses originating from incorrect conversion or use of measurement (kilo vs. pound, meter vs. feet, etc.) systems and non-safety events that lead to availability problems. This paper contains an analysis of a number of cases, concluding with some lessons learned and analysis of some alternatives to address this common-cause failure.

The Past and Present Measurement Systems Context

The world is becoming a more and more integrated global village, where the interaction and interconnectivity of systems is increasingly integrated. Thus, modern society can be viewed as a large socio-technical system hierarchically broken down into smaller socio-technical systems, all interacting together inside and within the planetary ecosphere. All this planetary scale co-evolutionary process brings huge challenges, given its complexity and the significant and potentially catastrophic influence that human activities have on this socio-technical system. These challenges will have to be addressed by engineers in a well-coordinated collaboration with social and political organizations in managing these socio-technical systems.

As mentioned by De Weck, Ross and Magee [Ref. 1], a key function of these complex socio-technical systems — and, as a matter of fact, of almost any system — is that of transformation (of matter, energy, information). Another important function of many systems is that of measurement with the purpose of quantifying and comparing.

Any transformation, including that of information, requires some energy or effort, while it has the potential for erroneous output due to the transformation process itself. Considering the scarcity of resources and the complexity of real problems that must be addressed [Ref. 1], it is unwise and inefficient for any socio-technical system to perform unnecessary transformations that have no value and exist only for legacy and historical reasons.

One large and totally unnecessary such problem is the use of different measurement systems by different socio-technical systems (states, governments and various commercial and non-commercial organizations). Thus, any inconsistency in communication and standards is bound to cause unnecessary problems at the interfaces due to transformation — an unnecessary effort at least — or to cause errors and possible system dependability (including safety) failures in the worst case. Living organisms, including humans, need to adapt to the changes in their environment in order to survive, and this adaptation of any living system is done mainly through a complex web of control loops. Whether negative or positive feedback or feed-forward, all these loops rely on various types of sensors to detect changes in the environment, and on actuators to output the organism adaptation response to the environment.

A fundamental characteristic of both sensing and actuating is that changes detected or effected are quantified by some form of intrinsic measurement. Measurements, in the large sense of the term, are innately and unconsciously performed by all organisms in nature. Humans have that ability as well, but they are the only ones that have become conscious of the importance of innate measurements and, with the advent of technology, have started to amplify and extend their ability to measure, both in depth as well as in breadth. That is, the ability of measuring and approximating quantities of matter using their own senses has been improved with the aid of more and more sophisticated measuring instruments. Not only have these tools improved the precision of measuring matter properties (size, volume, area, mass, etc.), but they have allowed measuring some properties that human senses were not able to detect at all (e.g., infrared and ultrasound waves). All these tools, though, were developed in connection and in parallel with the development of measurement systems, which are really nothing but sets of rules and conventions (about basic units of quantification and conversion), established and agreed to
within a social context. Because of the variability of the social context in time and space, there were historical and geographical differences between measures developed for the same purpose and matter property. Thus, until the Industrial Revolution, different measuring scales and units have been developed in different geographical areas, from which the best known was the British Imperial Measurement System and its variants, which are still in official use today in the United States and, unofficially, in Canada and Great Britain.

The evolution of human civilizations to the current global village was fueled in part by the co-evolution of science and technology, and the increase in sophistication of society in general, which relied on more and more sophisticated and varied measurement units that had to be standardized and harmonized into cohesive measurement systems. This was achieved for the first time in France at the end of the 18th century, when the metric system was introduced. Designed in the early stage of the Industrial Revolution, the metric system is a much better adapted and suitable measurement system for today’s technological society than any traditional system, including the British Imperial system. Therefore, the metric system has been gradually adopted as the official measurement system for most of the countries in the world during the last 200 years, leaving only a handful that have not yet adopted it, the most important, due to its size and influence, being the United States. Unfortunately, this slow transition to a ubiquitous measurement system has caused safety problems, and continues to do so today.

Learning From the Past: Accidents, Incidents and Near Misses
A Measurement Nuisance

The ability to adequately measure and process changes in the environment, and thereby deliver appropriately quantified adaptive responses, is vital for the survival of organisms, from amoeba to humans to the entire human society. Errors of measurement or transformation can lead to undesired consequences of various severity, from minor to catastrophic for the system. The following examples of undesired outcomes, ranging from inconvenience to catastrophe, caused at least partially by erroneous management (processing, conversion, interpretation, etc.) of measurement units prove this point.

Personally, this author has felt the nuisance of dealing with two systems in his daily life in Canada, where most people are, in the spirit of Canadian multiculturalism and bi-lingualism, capable of juggling in the same sentence both the official metric system and the unofficial, but practical — and still omni-present — Imperial System. On one hot Canadian summer day a couple of years ago, while accessing his personalized Yahoo page (see Figure 1, captured from the author’s computer monitor), the author noticed something unusual: Based on the temperature displayed by the weather java applet, the author realized that he should be almost boiling, and yet he was feeling quite well.

Notable Measurement Accidents and Incidents on Record

What follows is an account of the most notable accidents and incidents caused by using different measurement system-related errors.

The Gimli Glider Accident — In July 1983 [Ref. 2], Air Canada Flight 143, a Boeing 767 airplane, was flying from Montreal to Edmonton when it received low fuel pressure warnings in both fuel pumps at an altitude of 41,000 feet after only an hour of flight. Soon after, all engines stopped. Fortunately, the captain was an experienced glider pilot and the first officer knew of an unused Air Force base about 20 kilometers away. Together, they landed the plane on the runway, with only a few passengers sustaining minor injuries. This incident was due partially to a malfunction of the airplane’s fuel indication system, which forced the maintenance personnel to manually calculate the order to fuel the aircraft. They knew that 22,300kg of fuel was needed, and they wanted to know how much, in liters, should be pumped. They used 1.77 as their density ratio in performing their calculations. However, 1.77 was given in pounds per liter, not kilograms per liter. The correct number should have been 0.80 kilograms/liter; thus, their final figure

Figure 1 - The hottest day in Canadian History.
accounted for less than half of the necessary fuel.

Luckily, the cost of this accident did not include any human lives, but it did include some minor injuries, as well as the damage to the airplane and the effort expended in the investigation that followed.

**The Mars Orbiter Accident**

In September, 1999 [Ref. 3], the Mars Climate Orbiter, which was launched in December, 1998 as part of a climate research program, entered the orbit of Mars at an altitude of approximately 57 km, instead of the intended 150 km. This navigation error occurred because the software that controlled the rotation of the craft’s thrusters was not calibrated in SI units (Newton·seconds) as expected by the integrator, but in Imperial units (pound·seconds) (one pound force is equal to about 4.45 Newton). It is likely that the atmospheric friction destroyed the Mars Climate Orbiter. Based on NASA figures [Ref. 4], the total project cost was more than $300 million.

**The Tokyo Disneyland Roller Coaster Incident**

In December, 2003 [Ref. 5], at the Tokyo Disneyland’s Space Mountain, a roller coaster derailed just before the end of a ride, due to a broken axle. The axle in question fractured because it was smaller than the design specifications. Operating outside of its design specifications — thus placing the entire system outside the safety envelope — the axle broke due to excess vibration and stress. This happened because in September, 1995, the specifications for the coaster’s axles and bearings were changed to metric units. In August, 2002, the old design documentation based on Imperial units was used to order 44.14 mm axels instead of the needed 45 mm axels. Through the sheer luck of having the axle break at the end of the ride instead of the middle, there was no loss of human life and no injuries.

The only cost was that of minor mechanical repairs and the investigation that followed.

**The AIA Cargo Flight Near Miss**

In May, 1994 [Ref. 6], an American International Airways (AIA) aircraft flying from Miami, Florida to Maiquetia, Venezuela took off, flew, then landed overweight. The mishap began when the ground and aircraft crew misinterpreted the cargo weight units provided by the shipper in kilograms (43,328) as being pounds. The crew believed that the overall cargo weight was almost half of the real weight, and loaded the plane over its permitted safe capacity. Only during take-off did the pilot notice that something was wrong because the airplane was sluggish, with the climb to the cruising altitude taking more than an hour instead of the expected 30 minutes. The plane landed overweight in Venezuela where, after landing, it was noted that considerably more fuel was used (53,600 pounds) than estimated (46,600 pounds). The cost in this case was “only” more fuel burned, a flight delayed, some additional unexpected stress on the aircraft itself, and an investigation and lawsuit.

**Unrecorded Events: The Icebergs Below the Water**

Anecdotal evidence of quite a few other minor incidents caused by system failure due to measurement unit processing errors also exists. The author makes a note of the case of the software of a complex Naval missile combat system that, due to incorrect conversion of distance measurement units between old legacy software using the Imperial Measurement System and new software using the metric measurement system, calculated an incorrect trajectory intercept point. To make things worse, even the setup of the internationally agreed-upon system of units of measurement defined by the International Civil Aviation Organization (ICAO) (see Table 1) is a mosaic of measurement units. Although there are historical reasons for this mix-and-match bag of units, it is time to move on, as this promotes the use of an incoherent and confusing set of units. Although only anecdotal evidence of some incidents caused by this legacy heterogeneous mix exists, in the long run, it may be an accident waiting to happen.

Based on the author’s experience in safety engineering and assurance, confirmed by various safety publications as, for example, the ICAO Safety Management Manual [Ref. 7], the significant reported accidents are usually only the tip of the iceberg; thus, for each of the previously mentioned system safety accidents or incidents, there are many more — one major to 300 minor — based on the safety pyramid [Ref. 8]. These are unreported minor system failures due to the same common unnecessary cause: erroneous management (interpretation, conversion, processing). Also, considering that typically only a fraction of any system dependability failures are safety failures (i.e., hazards), there are even

<table>
<thead>
<tr>
<th>Quantity/Characteristic</th>
<th>Unit</th>
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<tbody>
<tr>
<td>Distance</td>
<td>Nautical miles</td>
</tr>
<tr>
<td>Altitude, elevations, heights</td>
<td>Feet</td>
</tr>
<tr>
<td>Visibility</td>
<td>Kilometers or meters</td>
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<tr>
<td>Speed, including wind speed</td>
<td>Knots</td>
</tr>
<tr>
<td>Vertical speed</td>
<td>Feet/minute</td>
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Table 1 — International Civil Aviation Organization (ICAO) Units of Measurement to Be Used in Air and Ground Operations.

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*Journal of System Safety, May-June, 2013*
more failures that “only” affect the availability or security of the system in cause.

In addition to the potential for loss of human life that some of these system failures have, there is also a considerable financial cost associated with damage of equipment, material and the environment. By conservatively extrapolating the cost associated with these well-documented accidents, we see that the total cost (including all non-reported incidents) could easily pass the billion-dollar mark, as only summarizing the cost of the major accidents described in this paper would be around half a billion dollars. Furthermore, if one takes into account a conservative incident-to-accident ratio of 300:1 [Ref. 8] and assumes a cost that is 100 times less per minor incident, the billion dollar mark is almost reached. The estimated loss is even higher if the overall system dependability-relevant (i.e., non-safety) cases are also taken into consideration — those impacting availability and security, and, therefore, overall quality. The bottom line is that all these unnecessary measurement-related failures have a considerable cost, thus being a difficult-to-justify factor in decreasing overall organizational efficiency.

**Metrification: Getting to a Safer State**  
**A Dependability Case for Global Unification of Measurement Systems**

The growth of technology and the resulting socio-technical systems makes the consequences of potential accidents increasingly devastating for health, safety and environment. Therefore, every reasonable effort must be made to reduce risk by reducing the probability of occurrence, which can largely be done by removing causes of these failures. Figure 2 contains a fault tree depicting three types of measurement conversion errors. There are various types of inadequacy of these measurements, from insufficient precision of the instruments used, to improper measuring units associated with the measurement, to errors in conversion between measurement units from the same system or different systems of measurement, or due to different reference systems. The errors that come from instruments cannot be completely eliminated, but can be reduced, while the errors related to measurement systems can be eliminated. More precisely, all of the following types of faults and resulting potentially hazardous failures can and should be eliminated, as soon as practically possible:

- Incorrect units input/output between two different measurement systems
- Incorrect conversion of units between two different measurement systems
- Incorrect conversion between units of the same measurement system

By applying ALARP (As Low As Reasonably Practicable) at the socio-technical-system level (country/state), the appropriate risk mitigation for the first three types of faults — which are also represented in the fault tree (see Figure 2) — would be the elimination of the cause and, hence, the hazard altogether. This means eliminating the need to convert from one measurement system to another by adopting a single common system that is universally accepted. Assuming that, sooner or later, all countries would have to adopt the globally accepted unique measurement system, there are only two practical courses of action:

- The transition to the global unique measurement system is performed as soon as practically possible
- The transition to the global unique measurement system is not performed, thus being indefinitely postponed

Through a simple comparative cost benefit analysis of the previously mentioned alternatives, it is evident that — assuming equal benefits — the second alternative has a higher cost because it includes the transition cost of the first alternative, as well as the costs of non-dependability (including non-safety) incurred by prolonging the dual measurement system status quo. Therefore, the cost of the first alternative, thus eliminating the hazard, is not disproportionate with the risk. Arguably, then, the best mitigation is the adoption of one measurement system to eliminate errors (see Figure 2) due to the use of two different measurement systems. In addition, if the choice for the unique system would be a purposely designed measurement system like the metric system, then at least the probability of error due to incorrect conversion between units of the same measurement system would decrease as the conversions are more intuitive and straightforward in the metric system.

**The Transition Challenges**

All that being said, one could wonder why the transition to the unique metric system was so long, and why it’s not completed yet. Based on various studies of social change and government policy, this kind of change to the fabric of a society is difficult [Ref. 9] to perform because:

- To begin the transition process, the leaders of the organization (be it a government or a corporation) have to convince many stakeholders to buy in
- Transition has a non-zero cost and nobody wants to bear it
- After the transition has begun, social and individual inertia, and the power of habit, have to be overcome

To make matters worse, these transition challenges create an additional negative side effect, as they make
it more likely that conversion errors will occur during the period of adaptation, simply due to the fact that the old and new systems of measurement will be used in parallel for a while, at least in people’s minds.

Despite these transition difficulties and the increased risk associated with the transition itself, there is no advantage in delaying the transition because:

- It was quite clear, at least for the last half-century, that eventually all countries would have to switch to the metric system, which is the international standard. The transition is a “necessary evil” for all.
- Delaying the transition prolongs unnecessarily the window of exposure of the socio-technical system (country, company) to a higher risk than would exist after the transition, which is also undesirable and unjustifiable.
- Transition risk might increase in time due to the overall increased complexity of a society viewed as systems of systems, where the multiplication of systems leads to an increase in the level of sophistication of the systems, as well as the increase of interconnectivity between those systems.

Some possible mitigations [Ref. 10] for the risks arising during measurement system transition have been proposed and used in practice: e.g., dual listing and signage.

**Metrcation Success Stories!?**

There are plenty of good and bad practical examples of how the transition should be done, as most of the world’s countries have completed, or are about to complete, this transition. It seems that countries that performed the transition from a variant of the Imperial Measurement System delayed the transition and also had more problems in performing it — despite even most of the biggest industrialized countries that were historically using the Imperial Measurement System, officially adopting and starting the transition [Ref. 11] to the metric measurement system: Britain in 1965, South Africa in 1968, Australia in 1969, and Canada in 1970.

The British metrcation process, although largely done, has been prolonged considerably and is still not fully complete. It may have been slowed because of irrational resistance due to historical, nostalgic and anti-European Union (EU) sentiments, as metrcation is sometimes perceived as something of French origin imposed by Brussels EU bureaucracy.

The South African metrcation [Ref. 11] has been completed as planned, without significant delays and hiccups, and is thus touted as one of the best examples of metrcation in recent history.

The Australian metrcation [Ref. 11] was quite successful and, even though it extended longer than planned, it is practically completed. Its geographical isolation from the U.S. is likely a helpful factor.

The Canadian metrcation [Ref. 11] process was also slower than envisioned, largely in part due to the persistence of a variant of the Imperial Measurement System in the U.S., with which Canada has intense commercial and cultural exchanges.

The largest and most influential country that has not yet officially started metrcation is the U.S. [Ref. 11]. At about the same time as Canada, the U.S. planned (and even had a law enacted) to perform metrcation, but for bureaucratic and political reasons, the start of the implementation was postponed.
leading to missed momentum, lost support and eventually dropping it altogether. The U.S. has not much choice in officially adopting the metric system, and its transition may be longer and more difficult the second time. It is encouraging that the need for adopting the metric system as the best available [Ref. 12] and globally accepted measurement system is already being recognized and some steps in that direction have been taken.

Conclusion
While diversity may be a desirable safety feature in some cases — such as redundant diverse channels architecture — it is definitely not desirable for measurement systems. The solution to the problem of different measurement systems has existed for a long time, but due to mostly historic legacy and social, cultural and institutional inertia, it was slowed at the expense of dependability (safety, availability, security, etc.) of many systems, with significant costs. A list of arguments has been presented, supporting global adoption of the metric system as the single measurement system, as both a way of eliminating risks with no benefit and unnecessary non-quality costs and their negative impact on the efficiency of the safety management system itself (reallocating system assurance resources from proactive value-added tasks to reactive damage control) and the entire organization (cost of realized risks). While diversity is an important safety mitigation principle, in some cases, it could have the opposite effect. There are many examples of unnecessary diversity due only to the legacy of history: Why shouldn’t all cars be driven on the same side of the road? Of course, that should be the right side of the road….

Disclaimer
The views expressed in this article are those of the author.

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