The Waddington Effect, C⁴U-Compliance, and Subsequent Impact on Force Readiness

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The writings of Sun Tzu (*The Art of War*) and Carl von Clausewitz (*Vom Kriege*) emphasize, repeatedly, the crucial importance of force readiness. A key factor in force readiness is the *availability* of its personnel, materials, and weapon systems. Another factor, equally important, is the degree of *clarity and correctness of any and all orders given*. Numbers alone do not accurately represent the strength of a military force – particularly if a large portion of the elements of that force are unavailable due to scheduled maintenance, unscheduled maintenance (i.e., repairs), or a failure to achieve an acceptable level of preparedness. And numbers alone may not be enough to overcome the confusion – if not outright chaos – that is sure to be created by orders that are unclear or ambiguous. The orders given (i.e., *"Someone had blunder'd"*) in Tennyson's poem, the "Charge of the Light Brigade," are but one example of the disastrous consequences of ambiguity.

One of the most important (and mostly overlooked) discoveries by British Operational Research groups in WWII was that of the *Waddington Effect* – a phenomenon induced by the improper conduct of maintenance. In this paper military force component availability, the Waddington Effect, and the determination of force effectiveness are addressed.

Central to the paper is a discussion of the development of *C^4U-compliant maintenance specifications*; i.e., specifications that are **c**lear, **c**omplete, **c**oncise, **c**orrect and **u**nambiguous. The vital importance, to force readiness, of what may seem to be – and what is too often treated as – the mundane and unglamorous task of the development and validation of such specifications will be described.

The paper concludes with a summary of recommendations for the mitigation of the Waddington Effect, the achievement of C^4U-compliant specifications, and

'Forward, the Light Brigade
Was there a man dismay'd?
Not tho' the soldier knew
Someone had blunder'd:
Theirs not to make reply,
Theirs not to reason why,
Theirs but to do and die:
Into the valley of Death
Rode the six hundred.'

Excerpt from *The Charge of the Light Brigade* by Alfred, Lord Tennyson

the subsequent increase in force readiness. It will also be noted how such "old" ideas may be employed to augment and improve the effectiveness of such "new" methods as Lean, Six Sigma, and Lean Six Sigma – concepts that have been widely adopted in the military, industrial, and governmental sectors. But first, however, let us take a brief look backwards – nearly seven decades ago to be precise.

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The dense morning fog slowly lifted and the rising sun began to illuminate an already bustling airfield. Two squadrons of bombers, of the Liberator class, sat arranged in precise formations, apparently – from all outward appearances – ready for another day's battle. On this day, like most any other during the war, each and every one of these lumbering beasts would be needed to conduct a truly effective mission. However, when those aircraft actually ready to support the day's mission had taken off, about half of the planes remained on the ground, impotent.

In July of 1943 the two British Liberator squadrons located at Ballykelly, Northern Ireland, consisted of approximately 40 aircraft. However, at any given time only about 20 of these were flight ready. Aircraft were down for any number of reasons, but mostly as a consequence of undergoing or awaiting maintenance – either scheduled or unscheduled – or perhaps waiting for maintenance personnel and/or spare parts. Conventional wisdom held that, if *more* preventive maintenance events were performed on each aircraft, fewer problems would exist – and potential problems could be caught and fixed – and thus the effectiveness of the fleet would surely improve. Conventional wisdom was, as is so often the case, wrong. It would take Conrad Hal (C. H.) Waddington and his Operational Research team to prove just how wrong.[1]

C. H. Waddington (1905-1975) is best known, today, as one of the first developmental geneticists – and as a person who did not believe that genetics, embryology, and evolution were separate sciences. But his interests and contributions covered a much broader spectrum. Those individuals involved in the field of Artificial Intelligence recognize him, *or should*, as one of the pioneers of the optimization technique designated as Genetic Algorithms. Those in the military recognize him, *or should*, as one of the leaders in the development of a new, unorthodox, and – at one time – highly suspect (i.e., by the military) approach to military planning, both strategic and tactical.

During WWII, Waddington was a key member of a newly formed group termed, by the British, Operational Research – a seemingly incongruous assignment for a scholarly animal geneticist. Yet it would be Waddington, and his colleagues, who would play a significant (and, sadly, mostly overlooked) role in defeating the Germans.

One of the many tasks that Waddington and his colleagues were given during Britain's fight for her survival was to determine how to increase the effectiveness of its Bomber command; e.g., to decrease the number of aircraft left on the ground each day. Rather than obediently and immediately taking the approach most people expected – i.e., either

See, **WADDINGTON EFFECT**, *pg. 18*

WADDINGTON EFFECT, *from pg. 17*

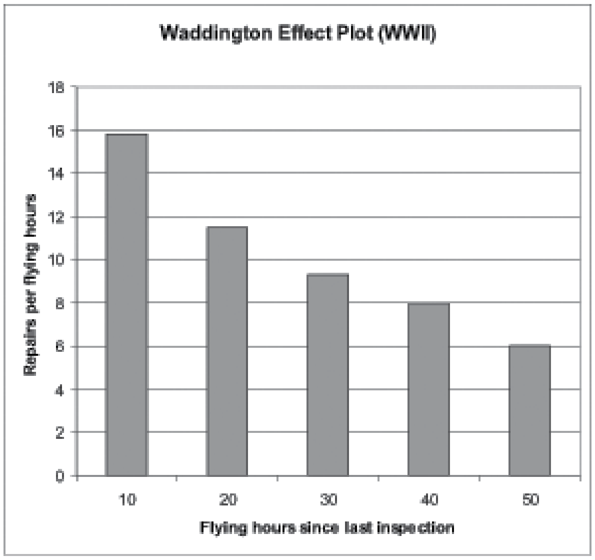

Figure 1. The Waddington Effect within Bomber Command

supporting the Coastal Command's plea for more airplanes or demanding more frequent and thorough preventive maintenance inspections – Waddington and his colleagues, instead, paused to examine the matter in detail and seek to identify the true cause of the problems being faced.

In other words, before scurrying about to provide a slick briefing on a scheme that might or might not work, Waddington and his team had the audacity to stop and think. They requested and analyzed the supporting data, talked with maintenance crews, and took time to carefully *and personally* observe actual maintenance events (a decision quite unlike that of too many "analysts" who prefer to remain in their warm and comfortable offices, poring over and processing data provided from "the outside"). Furthermore, rather than getting the wrong answer, or the politically correct answer, *fast*, these Operational Researchers trod the lonely path of seeking a proper, effective, and practical answer.

What the Operational Research Group discovered was a phenomenon that this author has termed the "Waddington Effect."[2] If the number of unscheduled repair events is plotted, along with the interval since the most recently scheduled event, the existence or absence of the Waddington Effect may be identified. Observe, for example, the plot of Figure 1. This is a graph of the number of aircraft repair incidents every 10 hours since the last *scheduled* maintenance event, as based on actual data cited in Waddington's classic book on Operational Research in WWII. As Waddington observed, the number of repairs ***increased*** after maintenance, ultimately settling down to roughly 6 repairs every 10 hours – *at about which time the next maintenance event was scheduled.*

The conclusion Waddington and his group reached, and one that seems clear from the plot, was, in Waddington's own words, that "inspection tends to *increase* breakdowns, and this can only be because it is doing positive harm by disturbing a relatively satisfactory state of affairs. Secondly, there is no sign that the rate of breakdown is beginning to *increase* again after the 40-50 flying hours, when the aircraft is coming due for its next [preventive maintenance event]."

In other words the Waddington Effect is defined as a "spike" in the number and frequency of *unscheduled* events "closely" following a *scheduled* event – followed in turn by a gradual decline in the a rate of occurrence of unscheduled events to a "more normal level," until a repeat of this same, troublesome effect following the next scheduled maintenance event.

Examining Figure 1, it may be noted that the frequency of unscheduled repairs rises almost immediately after a preventive maintenance ("PM") event. Yet, the purpose of preventive maintenance is – or should be – to reduce unscheduled repairs!

Waddington conjectured that either the preventive maintenance events were being conducted too frequently and/or the conduct of these events actually caused, rather than reduced unscheduled repairs. The solution proposed, and ultimately accepted, for the mitigation of the Waddington Effect was the development of improved maintenance events and their schedule (e.g., increasing the time between such events, identifying those components that needed to be either excluded or included in a given preventive maintenance event, the improved scheduling and allocation of maintenance personnel, *and the development of clearer, more complete, more correct, more concise, and less ambiguous documentation).*

Once these recommendations were implemented *the **effective** size of the British Coastal Command air fleet was increased by more than 60 percent!* In other words, a change in maintenance protocols and their documentation (as motivated by the identification of the Waddington Effect) was as effective (and far less costly or time consuming) as the allocation of an additional 60 percent more aircraft. *Perhaps the most surprising observation made by the British OR team, however, was the crucial role that documentation (e.g., maintenance specifications) had on the accomplishment of such results.*

Unfortunately, even those with a knowledge of the history of OR, may not be fully appreciative of the role that improved documentation – the development of what is termed herein as C4U-compliant maintenance specifications – played in the success of the effort described by Waddington. More specifically, the identification of the existence of the Waddington Effect, coupled with the development of improved maintenance specifications, can play a major role in the increase in the effective number of the components of a military force.

In general, the more weapons a military unit has, the more force it may *potentially* exert on the enemy. However, as noted, it is not the *absolute* number of weapons in inventory that determines the effectiveness of the fleet; rather it is the *effective* number of weapons *and* the speed at which they may be deployed. Yet, when generals and admirals (or CEOs) assess their strength, they may rely on a simple count of all the weapons (or factories and machines) in their "fleet" rather than those that are actually available. And availability, in turn, depends heavily on maintenance.

Unfortunately, there is little glamour associated with maintenance – *and even less in the supporting role of the preparation of maintenance specifications.* Compare, if you will, the number of news stories about exotic new weapon systems to those concerning maintenance, or even force readiness (which is determined in large part by maintenance). Even if the return on investment for an improved maintenance effort far exceeds that of the development of a new weapon system, it would seem – at least according to anecdotal evidence – that few officers will be promoted to the lofty grades of O7, or higher, based on their contribution to force readiness – particularly if it is accomplished via such "unexciting" efforts as improvements in maintenance and its supporting documentation.

One might think that WWII is ancient history and that the problems associated with preventive maintenance have been solved. A perusal of news stories with regard to military readiness, over the past decade or two, would prove otherwise. These stories also substantiate the fact that there is more involved in availability than just the number of "machines" and their maintenance schedules.

Consider, for example, the situation described in *Air Combat News* (March 11, 1997, http://www2.acc.af.mil/accnews/mar/970032.html). In his testimony to the House Subcommittee on Military Readiness, Senior Master Sgt. Dennis Krebs was asked why so many of the most experienced maintenance technicians in the Air Force had chosen to leave. Krebs cited the two most frequent responses: "tired of working extended shifts," and "tired of being away from their families." In short, they believed that they were being asked to do too much, with too little support.

In that same hearing, Col. William Carpenter, 1st Fighter Wing vice commander at the time, noted that the mission capable rate for his wing's F-15s had dropped below 81 percent. He stated that "We're flying increased hours with fewer aircraft and of the 67 aircraft assigned, our average number of aircraft possessed has only been 54 because we routinely have 10 aircraft undergoing major structural repairs, programming depot maintenance or contract field team work."

Krebs added that "Readiness is reduced due to lower number of aircraft our pilots can train in. Fewer mission capable aircraft results in fewer trained pilots." Reinforcing the above testimony is an excerpt from January 1999 Policy Brief #43, of the Brookings Institute.

> *Some types of equipment are in their worst shape in a decade.* For example, the mission capable rates or availability rates of Air Force aircraft have declined just below 75%, after being around 80% in the late 1980s and 85% in the early 1990s; and aggregate mission capable rates for Marine Corps equipment have dropped from 90% to 85% in the last five years.

While the topic of military readiness has been overshadowed by September 11, 2001 and the War on Terrorism, the situation is arguably not all that much improved (if any) over the past decade. The fact is that readiness in terms of weapon system availability is a function of:

- quantity and quality of personnel (e.g., pilots),
- spare parts,
- the quantity and quality of maintenance personnel,
- the complexity of the weapon system in question, and
- *the elimination or, at least, mitigation of the Waddington Effect.*

If attention is paid to these five issues, the readiness and overall effectiveness of the fleet will be – as demonstrated by Waddington's efforts – substantially increased. Conversely, anything that reduces force readiness will degrade the effectiveness of the weapons involved, and this must always be kept in mind.

Our focus, herein, is on the elimination – or mitigation – of the Waddington Effect. This may be accomplished by means of combining the lessons learned by the British Operational Research groups in WWII with those determined in conjunction with a study of the *art and science* of maintenance.

All too often maintenance activities and maintenance documentation are regarded as little more than "necessary nuisances." All too often the *science* that provides the foundation for an understanding and appreciation of maintenance and maintenance documentation is ignored or simply overlooked. It is, however, that underlying science, coupled with the discoveries made by British and American OR teams that serve to provide a systematic, scientifically-based methodology for significant and sustainable improvement in the performance of a military force, a production line, supply/logistic chains, and business processes in general. Too better understand this consider the three primary obstacles to the improvement of performance – of *any* system. These are:

- ***Unnecessary complexity*** (e.g., overly exotic weapon systems, incomplete, ambiguous, or downright incorrect maintenance specifications.)
- ***Excessive variability*** (i.e., in the performance of activities required in support of the mission of the system – where such variability may, itself, be an indirect consequence of unnecessary complexity, such as that in poorly written maintenance specifications.)
- A ***lack of vision*** (e.g., chasing of fads, embrace of the "quick and easy" approach, ignoring science, addressing symptoms rather than causes.)

All three of these obstacles play a role in failures to achieve any significant and (in particular) sustainable improvement in force readiness through enhanced maintenance. I will, however, focus – for hopefully obvious reasons – on just the first two obstacles.

The collection of ideas and lessons that serve to form the foundation of a systematically and scientifically-based approach to maintenance program improvement is designated, herein, as the performance of a "Waddington Analysis" in honor of the contributions of C. H. Waddington and his colleagues. Its scientific basis rests primarily on what has been termed the Three Fundamental Equations of production line performance where the "production line" may be that found in a factory, a supply chain, or a maintenance program.

These fundamental equations serve to determine the amount of "inventory" in a system (e.g., the number of aircraft requiring maintenance or repair), the cycle time of the system (e.g., the average time between the entry and exit of an aircraft in the maintenance activity), and the propagation of variability throughout the process. The specific formulas that serve to represent these equations may be found in the references and will not be repeated herein.[3,4]

See, **WADDINGTON EFFECT***, pg. 20*

WADDINGTON EFFECT, *from pg. 19*

An examination of these three fundamental equations serves to show that the average cycle time of a unit requiring maintenance (time it spends both waiting in a queue for maintenance and actually undergoing that event) is a function of both the *average time* required to undergo maintenance *and the **variability** about that time*. Consequently, if we are to reduce these downtimes and increase the *effective* number of weapon systems, one must find a means to reduce *both* the maintenance time *and its variability*. Equally important, if you are to mitigate the Waddington Effect, you must find the causes behind that phenomenon and eliminate or reduce it – and the analysis of the causes of the Waddington Effect, in both the industrial and military sectors, has shown that documentation plays a major role in maintenance time and the variability about that time. Fortunately, a practical and systematic approach may be used to accomplish a significant and sustainable reduction in (i) downtime, (ii) the variability about downtime, and (iii) the Waddington Effect. This approach has been designated, as mentioned previously, as a Waddington Analysis – a process that consists of the following steps:

1. The development and validation of C^4*U-compliant maintenance specifications.*
2. The organization of the workspace (designated within the Lean Manufacturing community as CANDO, or 5S) so as to *both* reduce clutter *and* support the C^4U-compliant specifications developed in Step 1.
3. Optimization of (i) the number and allocation of maintenance technicians; (ii) the level of spares and supplies, and (iii) the physical location of spares and supplies.

Optimization models in support of the accomplishment Step 3 have been developed, published, and explained in detail in the open literature.[5,6] In this paper, however, our focus will be restricted to the conduct of Steps 1 and 2.

- ***Step 1: Development of C4U-compliant specifications***.
  a. Cite the precise goal or goals the maintenance effort in question is intended to accomplish. If you cannot cite these, clearly and unambiguously, it is unlikely that the resulting document will adequately support the primary intent of preventive maintenance; i.e., to avoid unscheduled downtime. (In discussions with numerous maintenance managers, the author found that the specific goal of PM specifications could not be cited more than 60 percent of the time.)
  b. Recognize that the developer of the maintenance specification must be thoroughly familiar with the system or systems for which the specification is to be designed. (Too often it is assumed that "anyone" can develop a specification.)
  c. Develop the initial specification, and then refine and validate it by means of a series of "dry runs" (i.e., carefully structured practice runs.) Repeat these until the developer believes no further improvement is possible.
  d. Once the developer is satisfied with the specification, have someone other than the developer engage in additional dry runs. (Despite what the maintenance expert and specification developer may think, vital steps invariably will be omitted, and ambiguities will be present. These are best caught by a novice in his or her attempt to follow the steps of the specification.)
  e. Employ the previous two steps to eliminate unnecessary steps and avoid unsafe actions. Document every known deviation, ambiguity, and problem encountered, and revise the specification accordingly.
  f. Repeat the previous three sub-steps until the specification is deemed safe, credible, and effective – and the need for any pass-down (i.e., to a subsequent shift) or explanation is, ideally, eliminated.
- ***Step 2: Workspace organization***
  a. After completing the previous step – ***and not until that step has been completed*** – take any actions necessary to ensure the workplace is organized and uncluttered s*o as to support the final, refined specification.* Workspace organization, in turn, is accomplished by what is now termed CANDO or 5S in the Lean Manufacturing community.[7]
  b. Monitor the performance of each PM activity and revise and refine the associated specifications (and any subsequent changes that may be necessary in workspace organization) whenever necessary. No matter what type of system is being maintained, continual improvement in PM specifications is a necessity.
  c. Finally, if PM events are calendar-based (e.g., scheduled every week, every month, etc.) recognize that calendar-based maintenance is motivated by convenience. There is no reason that an event conducted every week may not be equally (if not more) effective if conducted, say, every 8 or 9 days. In fact, one of the findings in the effort conducted by Waddington's group was that PMs were being scheduled *too frequently.* Furthermore, each PM event should be monitored and documented so as to determine if there is truly a need for the inclusion of a given component that has been specified to be replaced or repaired – or if a component that is not slated for replacement or repair is seen to frequently be in need of attention. When such instances are noted associated changes in the PM specification (and, if necessary, workplace) should be considered.

The above procedure should assure the development of a maintenance specification that is C^4U-compliant. The ultimate determination of whether or not the procedure has indeed produced such a specification may be accomplished by the determination of the achievement or non-achievement of certain goals, including:

- The specification should be capable of being conducted successfully by any other reasonably competent technician without, ideally, the need for input from any source other than the specification.

- The specification must be shown, to the degree possible, not to induce unscheduled downs – and must satisfy all safety, ergonomic, and human factors requirements.
- The specification must be shown to enable the right components to be examined, replaced, or repaired at the right time by the right people using the right tools as located in the right place and applied in the right order.
- The conduct of the specification must make a measurable and positive difference. This is typically noted by improvement in system availability, mitigation of the Waddington Effect, and improvement in the M-ratio. The M-ratio, in turn, is the ratio of the time consumed by scheduled downs (i.e., PMs) to that consumed by unscheduled downs (e.g., repairs, recalibrations). The M-ratio should be on the order of 9 or more (i.e., no more than 10 percent of the downtime of a system should be due to unscheduled events).

Those organizations that have adopted the above procedures have found that they have indeed eliminated or mitigated the Waddington Effect and achieved substantial improvements in overall performance (e.g., reduced cycle time, increased *effective* "fleet" size, and less uncertainty in the estimates of PM duration.) Furthermore, they have reported that their maintenance technicians experience a considerably less stressful work environment – with a subsequent reduction in personnel turn-over.

The most improvement has been noted in those organizations who have not only identified the Waddington Effect and employed Waddington Analyses, but who have clearly demonstrated, through both words and actions, that they place a high value on their maintenance program and recognize (***and reward***) the importance of the development of C^4U-compliant maintenance specifications.

The necessary training of employees in the identification of the Waddington Effect, the development of C4U-compliant specifications, and the subsequent organization of workspaces may be accomplished in no more than a week-long training event – followed by a reasonable (and unobtrusive) level of the monitoring, oversight, and support of the maintenance technicians.

As a final note it should be emphasized that the identification of the Waddington Effect, development of C4U-compliant specifications, and employment of a Waddington Analysis are activities that should – in any organization – be a prerequisite to such "Lean Manufacturing" activities as CANDO or 5S (i.e., workspace de-cluttering and organization.) The incorporation of the approach discussed herein, with such workspace organization efforts, has been shown to provide a significant improvement over just that of conventional workspace organization.

Resources

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Biography

Professor James P. Ignizio received the Ph.D. in Industrial and Systems Engineering from Virginia Tech. He holds the position of Louis A. Beecherl Professor of Engineering at the University of Texas – Pan American. Ignizio is the author of nine books, including *Optimizing Factory Performance*, McGraw-Hill Publishing, 2009, upon which much of this paper is based.

Statement of Contribution For:
The Waddington Effect,
C^4U-Compliance, and Subsequent
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By Professor James P. Ignizio, Ph.D.

Military readiness is a matter of interest, or should be, to virtually anyone in the military sector or to its contractors. Maintenance plays a major role in readiness – but one that is not always fully appreciated. Even less appreciated is the *seemingly* mundane and decidedly unglamorous role that maintenance specifications play. The paper is intended to motivate more attention to maintenance, couple maintenance with force readiness, describe the vital role that maintenance played in the origination of Operations Research (i.e., Military Operational Research as developed in the UK during WWII,) and present what should be (to the reader) two new concepts in maintenance: the Waddington Effect and Waddington Analyses.

If this description seems a bit "off the wall," please note that a previous paper that I had published in *PHALANX* was also considered "unusual." That paper, "Systems Stability: A Proxy for 'Graceful Degradation,'" did, however, receive the John F. Walker award in 2000 and has motivated numerous R&D efforts since then.