Total Ownership Cost (TOC) Avoidance with Proper use of 3-D Modeling and Simulation Tools for Human Machine Interactions

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Abstract

In today's world, 3-D modeling and simulation (M&S) capabilities have provided engineering and design efforts with powerful and useful tools. These M&S capabilities allow engineers and designers to gain a "first look" at the interaction between the human element and the workplace environment. Proper utilization of M&S in the preliminary and detailed design stages as well as the in the design review process has saved significant amounts of money. The more notable reductions in total ownership costs (TOC) occur when human element deficiencies are discovered early in the design process. Furthermore, with the early identification of human element deficiencies, solutions can be achieved before any construction activities take place. Unfortunately, 3-D modeling and simulation is not a panacea. As the technology exists today, the applications are still somewhat limited.

INTRODUCTION

Over the last decade, a variety of computer based tools have become available to designers that allow better control and management of their design efforts. The need for better tools has arisen from the competitive nature of today's markets where rapid design development and short delivery times of high quality products is a must (Karwowski et al., 1997). Designers and builders have turned to tools such as three dimensional computer aided design (3D CAD) to aid them in their quest. Use of 3D CAD has provided virtual environments where design team members can get an early picture of the fruits of their design efforts.

Another tool that has aided in the production of high quality designs, is the integration of human factors engineering as a discipline on design teams. Along with 3D CAD, have come computer software packages that allow more sophisticated 3D simulation of human operators or maintainers and thus provide a means of evaluating the work place design from an ergonomics standpoint. These software packages have provided the human systems specialist with invaluable tools for assessing a design for operability and maintainability. The software usually allows dimensioning of human models so that a human representative (that matches the user population) can interact with the proposed design. The various computer modeling and simulation (M&S) tools also allow human systems specialists to assess items like reach envelopes, lines of sight, human postures and overall access and egress. Other features of such computer tools include the ability to conduct workload analyses (traditional time and motion studies) and biomechanical analyses of lifting and lowering tasks. Since these evaluations are done while the design is underway, these computer tools allow changes to be made to the design when deficiencies are found and they allow for the development and testing of potential solutions.

The objective of this paper is three-fold, first to show where, in the design process, M&S evaluation tools can be used for human factors and ergonomics purposes. Secondly, to provide examples of where they have been used successfully. Finally, suggestions will be given for further M&S technology improvements that would allow optimization of human system integration.

CONCEPTUAL DESIGN PHASE

Prior to the actual use of M&S, there are numerous decisions that will take place during the conceptual design phase that will influence how successfully human factors and ergonomics can be assessed using these tools. For example, certain philosophies will be decided upon concerning operations, maintenance, safety, and staffing. Operational philosophies will influence the level of automation used for the various systems. The operational philosophy will also influence the sophistication level of the crew in terms of the desired personnel's skills, knowledge, and abilities. Maintenance philosophies will influence equipment and system reliability targets as well as where equipment redundancy will be employed. Additionally, decisions will be made about who will perform the maintenance tasks (e.g., existing personnel or contractors), or where the maintenance will occur (e.g., in place, in a shop, on-shore). Safety philosophies will affect escape, evacuation and rescue measures, fire-fighting strategies, hazardous material usage, and personnel issues such as limiting the amount of weight a person shall lift. Staffing philosophies will affect the number of personnel, their qualifications, responsibilities and even their work hours. All of these philosophies will impact the design, both hardware and software, as well as the evaluation criteria used by the human systems specialist or designer. Additionally, during the conceptual design phase, the role of human systems integration will be examined to produce the human factors engineering standards for the design. These standards will provide modelers with important information with regards to the design of the various human-machine interfaces. Providing such specifications will assist modelers with the production of a library of standard equipment or component designs that would meet human factors criteria. For example, the library might contain a standard stair or ladder, a standard console height or configuration.

PRELIMINARY DESIGN PHASE

During preliminary design, there will be further definition of overall operational requirements, critical system features, and maintenance philosophies of the system, structure, or vessel. During this phase, general or preliminary arrangement drawings will be prepared to provide a first look at equipment arrangements and orientation, initial space layouts, workflow or production patterns, and egress paths, including both normal and emergency personnel movement paths.

Equipment Arrangements and Orientations

With regards, to equipment arrangement and orientations, the human systems specialist can use the computer model to assess a variety of operational and maintenance issues. It is important to determine whether the initial layouts will optimize the conditions under which personnel will be working. For example, have areas with visual communications requirements been located such that clear lines of sight are possible? Line of sight is particularly important for both flight and crane operations where personnel in control rooms or crane cabs interface with personnel working on the deck. While the particulars of these operations will be worked out in detailed design, initial assessment can be conducted using the computer models in preliminary design to identify any potential design deficiencies. For example, evaluations of crane operations in preliminary design are possible by simulating the needed reach radii for the crane boom. At this early stage, various options can be tried with regards to crane placement in order to determine the best location, while avoiding obstructions. For control panels, the human systems specialist and design team members can use the computer model to evaluate the local panels placement. Local control panels should be orientated in such a way that facilitates personnel working together with one person at the panel and another at the equipment. Panel orientations can be proposed that provide good lines of sight between the panel and related equipment. In areas where a number of personnel must work concurrently, the space allotted in the model can be reviewed to see if there is sufficient room to accommodate the personnel and any necessary equipment for various operational and emergency conditions.

Workflow Patterns

During this phase of design a more detailed maintenance philosophy will be developed. This will allow the human systems specialist to work with designers to identify and assess the following based on information from the computer model:

1. With the various equipment skids or groupings, what will be the best orientation of the equipment with regards to repair, removal, or replacement?
2. How will repairs and replacements be accomplished? Are special design features required to accomplish these tasks like hatches, access panel, or lifting equipment?
3. What means (rigging, handling and carts) or requirements (pad-eyes, monorails, etc.) are needed to allow the maneuvering of equipment or loads around the facility or design?
4. What are the requirements for maintenance shops and equipment storage and have these spaces been allotted?
5. Where is the best location of these spaces with regards to the equipment?

It is important to answer these questions for the purposes of assessing equipment location and arrangement and workflow patterns. Proper equipment placement with regards to the repair facility will allow the worker to get the equipment to the repair facility in a timely manner, therefore reducing the mean time to repair (MTTR). Proper selection and placement of lifting devices will decrease the potential for personal injury, further damage to the piece of equipment, damage to other piece (s) of equipment, or damage to the structure during the equipment removal process. These early evaluations can represent a TOC saving to the owner by avoiding costly rework. If the design deficiency is not to be reworked, the existing design will have to be accepted and worked around for the life of the facility, therefore increasing the TOC.

Access and Egress

It is crucial at this early stage to evaluate the sufficiency of the access ways for both equipment and personnel. Using M&S, the human systems specialist, as well as other design team members, can make an initial assessment about where equipment and passageways might be placed. Additional assessment will include the ability to move equipment, goods, supplies, and people through spaces and passageways in a safe and efficient manner. An example of the benefit of such analysis was shown by a design team reviewing the food storage areas on general arrangement drawings for a new ship design. It was discovered that several food storage areas were not placed in close proximity with galley. Using a computer model, the galley spaces and food storage areas were further analyzed and it was identified that the freezers and dry goods storage were the furthest away from the galley. Based on a workload analysis that included a review of frequency of use of food stuffs, distance from the galley, amount of stores used per meal, and the size, type, and weight of the foodstuffs, the food storage areas were relocated. This resulted in a decrease in food transportation and preparations times, increasing the efficiency of the workers time and efforts. An additional benefit included a reduction in the exposure to personal injury by personnel not having to lift and carry heavy objects distances longer than necessary. Use of the computer model provided a means for assessing the influential factors and for trying different design options.

M&S also provides an effective tool for reviewing the egress paths personnel would use under normal and emergency conditions. These paths should be set early in a design project with routes that ensure rapid and unobstructed escape routes. Routes can be proposed that either avoid or minimize travel through hazardous areas (e.g., high noise areas, areas where there are elevation changes, areas where chemical hazards may be present). The computer modeling capabilities can be used to block designers from placing anything in these areas by using a computer tool called obstruction boxes. These boxes prevent anything (e.g. equipment, piping, storage lockers) from being placed in certain zones within the computer model by making certain coordinates unavailable to designers via the software. Obstruction boxes can also be used to reserve areas in the model for equipment pull spaces, for passageways for personnel egress, and for access paths for the movement of equipment, goods or supplies. This will help eliminate costly design errors and rework later in the design effort. For example, if it was known that a heat exchanger tube bundle will need eventual replacement, the designer can add an obstruction box that provides clear space for pulling the bundling. Consequently, no one on the design team can access that reserved space in the model for the addition of piping, cable trays, or any equipment, which would interfere with the bundle removal, once the obstruction box, is defined.

Vehicle and equipment paths would also be reviewed to determine if all possible vehicle or equipment configurations could negotiate ramps, turning radiuses, clearances, etc. On a new ship design, M&S technology was used to evaluate the preliminary design of the upper and lower vehicle decks. It was discovered during this preliminary design review that some of the larger vehicles had a larger turning radius then the initial design provided for. Without detection this design would result in substantial amount of wasted time, damage to the vehicle (s), and damage to the ship. Early detection allowed designers to correct the deficiency. It was estimated that the identification and correction of this design deficiency resulted in a significant saving in TOC.

All these steps are important because the proper placement of spaces and equipment facilitates not only the efficiency of work patterns, procedures and personnel movements. Additional impacts can been seen with work quality, worker productivity, overall safety of equipment and personnel, and operational costs. All these factors have a direct impact on TOC.

DETAILED DESIGN PHASE

After the preliminary designs have been approved, a more detailed design is created. At this point, human factors and ergonomics attention is drawn to more specific design aspects such as the operation, maintenance, placement, arrangement, and orientation of equipment, workflow, and egress paths. It is critical to finalize certain human factors engineering details in relation to the users anthropometrics, line of sight requirements, workflow/traffic patterns and operational and maintenance envelopes. These issues are vital for properly designed human machine interfaces.

Anthropometric Issues

Anthropometry is the science of measurement and the art of the application that establishes the physical geometry, mass properties and strength capabilities of the human body (Roebuck, 1995).

The data on human dimensions is presented in terms of specific anatomical features (e.g., eye height, stature, elbow resting height) and postures (seated or standing). Anthropometric data is often reported in percentiles where the 5th percentile indicates that only 5% of the study population will have smaller dimensions. The 95th percentile indicates that only 5% of the study population would have larger dimensions. Standard HFE practice is to provide a design that will accommodate up to 95% of the expected user population.

During detailed design, the human systems specialist will use the model to ensure that issues relating to anthropometrics are met. For example, for a manually operated valve, the human systems specialist would evaluate whether the placement and orientation of the valve was suitable for most personnel (95%). In order to determine this, the human systems specialist would not only use appropriate anthropometric data, but would also evaluate other factors such as modes of operations (e.g., frequent, infrequent, emergency use only) and maintenance requirements. Knowing the operational mode (s) of a valve provides information for valve placement. Frequently used valves or those for emergency purposes will need to be located in places easy to access. Understanding a valves' maintenance requirements provides information on the amount of space that will be required for the maintainer, this is commonly referred to as the maintenance envelop. User anthropometrics, such as the elbow resting heights of the 5th and 95th percentiles users provide additional information for proper valve placement. Additional criteria would include ensuring the wheel or lever is oriented out of the egress path and any related gauges or displays associated with the operation of the valve are visible. All these criterion need to be considered for the optimum placement of the valve and it's height while maximizing the biomechanical advantage of having the wheel or lever where workers are the strongest, at elbow level.

Another example of where the use of anthropometric data is important to the maintenance aspects of design involves personnel entry hatches or man-ways. Prior to any assessment, the human systems specialist will identify any unique aspects associated with a work task or the user population. For example, if the task, such as tank cleaning or inspection, must be conducted in a cold environment or wearing a breathing apparatus, then the additional bulk of these items must be considered during the assessment. Since the human system specialist must identify all potential personnel factors, it would also be important to determine if the maintainer must wear a harness or carry tools or equipment when entering the tank. Using the computer model, the human systems specialist would determine if the manhole or hatch would be large enough for a 95th percentile male wearing cold weather clothing, a breathing apparatus and a harness. With knowledge about dimensional allowances for "arctic" type clothing, the breathing apparatus, harness and any other equipment, mannequins can be developed using the expected users population anthropometric data to evaluate "fit". If personnel did not fit, then design alternatives could be simulated. If it is not discovered until after construction that personnel (and their gear) can not fit through a manhole, a change to accommodate these requirements, would prove costly. At a minimum, a back-fit would need to be designed. It would also be possible that in order to incorporate the backfit, the original manhole would need to be removed and additional structural reinforcement for the new manhole would be required. Incorporating the change could also result in equipment or system downtime. All these factors will increase the total ownership cost (TOC) associated with the design.

Line of sight concerns

Line of sight must be further evaluated during detailed design. While initial reviews relating to this issue may have been conducted during preliminary design, with the progression of the design, the model can be used by the human systems specialist to confirm that safety critical lines of sight are unobstructed. Returning to the earlier mention of flight operations, during one design effort, worker line of sight was identified as a critical safety issue. It was established during preliminary design that a worker would be required to look out a window to view ongoing flight operations. Using the computer model, it was determined that a portion of a structure obscured a small segment of the landing area thus blocking the line of sight between the flight control staff and the flight deck. This discovery was possible because the flight operations control room was considered a critical work center, and the structures outside the control room including the flight deck areas were electronically modeled. It was by using M&S line of sight capabilities that the deficiency was identified. Had this gone unidentified, the likelihood of incidents would have been high and any backfits to correct the problem would have proved quite costly.

Workflow and Traffic Patterns

In addition to line of sight concerns, the human systems specialist will need to conduct detailed reviews relating to workflow and traffic patterns. The human system specialist would evaluate not only traffic patterns relating to the normal and emergency work patterns of personnel, but also would review areas where special equipment might be used. The importance of such reviews can be seen in the following example. On a new design, forklift operations were modeled in one of the cargo storage areas. This model included forklift paths, storage areas, recharging stations and general operations. Several design deficiencies were identified. 1) Due to the enclosures around a cargo elevator, the forklift's tines could not reach far enough into the elevator to safely place or remove pallets. The solution was to design a heavy-duty ramp to allow the forklift to get closer to the elevator. 2) A forklift with its load raised too high would hit several sprinkler heads and lighting fixtures. The solution was to raise the lighting and sprinkler systems. 3) The forklift could not successfully maneuver around in some of the various cargo storage areas because the aisleways were too narrow. M&S identified these design deficiencies at a stage where they were easily correctable. Savings in TOC can be seen from an improved productivity and workflow standpoint as well as reduced costs associated with corrective maintenance and equipment replacement (light fixtures and sprinkler heads and piping). These lessons learned were then transferred to the other cargo storage areas to eliminate similar design errors, therefore, increasing the level TOC avoidance.

Operational and Maintenance Envelopes

In addition to workflow and traffic patterns, the human systems specialist will ensure, using the computer model, that sufficient room has been provided in and around equipment to accommodate both operations and maintenance personnel doing their jobs. Providing sufficient access is very importance since it is a well-established fact that tasks where equipment is difficult to reach or access take more time to complete or in some cases, preventative maintenance may become neglected. In other words, ease of access can actually determine whether personnel will maintain a piece of equipment. Knowing this, on one new ship design, M&S technology was used to evaluate maintenance clearances for items in an equipment space. The equipment was modeled using generic representations of the final equipment configurations (i.e., providing similar shape and size in square and cubic footage). A mannequin was created, to represent the 95th percentile male, with requisite clothing and equipment, and maneuvered around the space and put into various postures to mimic someone actually performing preventative or corrective maintenance. Numerous areas were identified where the mannequin could not access the required equipment or component. Had these deficiencies gone undetected, the ship owner would see an unexpected increase in mean time to repair (MTTR) of this equipment, as well as an increase in maintenance costs due to inadequate access. The other possibility is that the preventative maintenance might have been neglected. The lessons learned about inadequate maintenance clearances were then transferred to other equipment areas of the ship, therefore increasing the benefits of this discovery.

Other Human System Concerns

In this paper, numerous examples of possible human interaction assessments of a design using M&S have been discussed, but the coverage of potential interactions is not comprehensive. There are factors, which do not directly indicate a human machine interaction but do indirectly impact the human's capability to safety and efficiently perform their duties or move about the design or be protected from hazards. The text below contains other areas or concerns that the human system specialist should review using M&S.

During design reviews, the human systems specialist should pay particular attention to the routing of piping. It should be ensured that the piping does not obscure egress paths. Checks for overhead clearances and tripping hazards should be made. Using the model, the human systems specialist can evaluate other access concerns, making sure that piping, piping supports, or other structures do not block access to other equipment. Additional review features include items such as ladders, stairways, and that they have clear and adequate pathways. The model can be used to check that piping or cable trays do not block fire sprinkler systems or interfere with lighting. Checks can be made that piping containing hazardous material is not running through personnel areas or other areas containing potential reactive agents or that such runs are minimized.

The human systems specialist can also use the model to evaluate safety issues. Tripping hazards (i.e., knee knockers and coamings) can be identified and modifications suggested. The human systems specialist can identify any possible personnel collision points ("T" intersections, equipment movement down frequently traveled personnel aisleways, doors that swing into egress paths) and request changes to minimize such problems. The sufficiency of passageways for passing stretchers and gurneys on route to a hospital or sick bay can be checked. Identified problems can then be addressed by design modifications or by designating particular routes for such situations. The space requirements for the hospital, galley, or messing areas can be reviewed and if necessary, crude models of the furniture and equipment can be placed to fine tune the evaluations. Using the computer model, the human systems specialist can check firewater or foam hose reel locations and ensure that their orientation allows personnel access to them. Additional hose reel concerns are that they have been placed within sufficient reach of the intended areas of concern and that the reel is positioned for ease of operation (i.e., reducing the potential for kinks in the hose). The accommodations design and layout can be reviewed via the computer model to check that normal and emergency access requirements have been adequately address. The model can also be used to review office and berthing spaces. One significant benefit of using a computer model is that a design team can look at personnel flow throughout the entire design or sections of the design and make modifications while the design is still in a "virtual" state.

WHERE SHOULD 3D M&S CAPABILITIES GO?

At present, the majority of 3D CAD tools provide the users with qualitative evaluation capabilities. The types of issues that can be evaluated include user anthropometrics, line of sight concerns, access, workflow and traffic patterns, etc. However, some 3D M&S packages contain basic human factors and ergonomic quantitative design analysis capabilities such as evaluation tools for lifting and lowering tasks, energy expenditure, and time and motion studies. These are helpful to the human system specialist , but their use is not widespread. Of the tools that do exist, more advanced and comprehensive analytical capabilities are necessary (Feyen, et al., 1999) to fully analyze and optimize the human machine interface.

Additional assessment/analysis techniques that need to be developed and/or incorporated into existing software include improved biomechanical and ergonomic analysis tools. These tools will help calculate and assess the ergonomic costs associated with the operation or maintenance of a piece of equipment or component. Enhanced biomechanical and ergonomic assessment is important to allow designers and Human systems specialists to manipulate a human model to analyze both the workers' posture and the activity being performed. Existing ergonomic and biomechanical assessment capabilities include the analysis of some lifting, lowering, and carrying activities but not for holding, pushing, pulling, grasping, and turning as in the case with valve operation.

Ergonomic and biomechanical analyses need to include the physiological and psychophysical relationships between the human and the work piece, tools, workstation, and work environment (Smith, Ayoub, McDaniel, 1992). These relationships offer the calculation of acceptable limits for holding, pushing, pulling, grasping, and turning activities with respect to weights, forces, and frequencies. The establishment of these limits will allow designers to determine if an object (material or equipment) can safely be moved or operated manually, by the expected user population. For example, if a valve were located well below the optimum height, can an operator manipulate the wheel or lever without injury? If this valve is a critical piece of equipment, this evaluation is essential. Advanced assessment capabilities would analyze the workers posture (stooped or kneeling) and be able to calculate the maximum forces that can be generated, by the worker, from that position (Annis, McDaniel, & Krauskopf, 1991). The assessment criteria would be based on existing research on human strength capabilities and limitations. Once this force is calculated, it could then be compared to actual force requirements in an effort to determine whether he valve can be operated safely.

Another biomechanical/ergonomic assessment capability should be the ability to model the human in total (entire body) or in segments. This would allow evaluation of stresses placed on the entire body, or the extremities. Such analysis would predict where tasks, in particular postures, might result in discomfort, acute injuries (back strain) or repetitive motion problems (e.g., tendonitis, carpal tunnel syndrome). Knowing that the human body can bend or twist in a certain manner does not mean that it is practical to assume that a given task can be performed safety, comfortably, and efficiently. Postures approaching the limits of range of motion or capabilities would need to be analyzed further to determine what impact they may have on the performance of the worker's duty. For example, if a worker is required to squat and twist their body for a long period, because of restricted access, in order to perform a maintenance task, pain and discomfort would set in. Several things may occur; 1) the worker may continue despite the discomfort, 2) the worker will take frequent breaks, or 3) the worker will finish only the minimum amount necessary so they can leave the space or 4) may become injured. Why is this important? If personnel must work in awkward and painful constrained positions for long periods of time, they are more likely to suffer pain, discomfort, injury, or illness. This exposure may affect their ability to perform the task correctly, which in turn may have an adverse effect on the system functioning or reliability. If the worker suffers an acute or chronic injury, this will effect their ability to perform other required tasks. It could even affect their availability for light or limited duty. Additional concerns include the increased time for the task to be accomplished if the worker has to take frequent breaks, due to the sensations of pain or discomfort. This will impact MTTR as well as the systems operational availability.

Further enhancements of M&S could permit human systems specialists to develop comfort and functionality indices. The indices would be based on information obtained about the equipment's maintenance philosophies and from previous maintenance records. The indices would also require estimates for various maintenance activities to determine maximum limits for various postures. This would allow designers to conduct “what if” analyses of different methods and procedures to determine the optimum design.

CONCLUSION

Numerous success stories have been discussed here about the use of M&S with regards to the human machine interface. These real life examples have also demonstrated that the proper application of Human Factors engineering can play a major role in all design phases of a product, system, facility, or vessel.

The role of M&S and the human machine interface is not just applicable to large-scale design projects such as offshore platforms or ships but also applies to smaller design activities as well. The same assessment and evaluation techniques used to design an entire offshore platform can be used to design a ship's electrical distribution panel. Both designs have operators and maintainers associated with their operation, each having their respective requirements for working envelopes, anthropometrics, line of sight, working postures, and access concerns.

Human systems specialists with their expertise on the human, their capabilities, and limitations, and requirements are extremely valuable members of the design team, as presented in the examples. One of the most powerful tools the human system specialist can employ is M&S. This is because M&S serves as an excellent tool for evaluating a design and it allows the human system specialist to demonstrate the impact of ergonomic requirements to others. M&S also provides a means for trying different alternatives in cases where improvements are deemed necessary. The "early window" into design combined with the ability to weigh design alternatives, allows human system specialist to provide a human centered design at a reasonable cost.

As 3D CAD technology grows, with respect to Human Factors Engineering, and includes some of the suggested improvements, its impact will be far more impressive then presented here. Fully functional electronic models with comprehensive human factors and ergonomic analysis capabilities are realistic expectations. These capabilities will optimize any new system design from the perspectives of human performance, human factors, ergonomics, safety, staffing, training, and of course the ultimate goal ***Total Ownership Cost Avoidance***.

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