Automation of the design process

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ABSTRACT: Over the last 40 years ever more sophisticated computer hardware and commensurate developments in software have enabled much design to be computerised. More recently systems integration has allowed software to automatically pass data from package to package. This has effectively automated elements of the design process.

As with all developments there have been advantages and disadvantages. Automation has brought great efficiency gains and has removed many of the tedious aspects of design, but at what price? Generally designers resist the notion of automatic design and prefer to talk about efficiency of processes and the computer doing the “number-crunching”, leaving the designer “free to think”. However, despite the reluctance to acknowledge the phenomenon, [at least partial] automation of the design process has arrived. The reason why designers don't like the notion of automatic design is that automation implies loss of control and all designers should be (and are) fully responsible for all aspects of the process however efficient/automated it becomes. Whatever the semantics, there are major issues surrounding process automation and this paper explores the pros and cons in detail.

The benefits of design automation to the industry, and society at large, are considerable. Design is now faster and more accurate, and the whole process has been significantly enhanced by the available technology. However, it can be argued that the more automated the design process becomes, the more the designer loses the intrinsic feel for an appropriate solution. There are at least two documented significant structural collapses that have been, at least in part, attributed to computerised design. Lessons from both these failures are discussed in the paper. There are significant implications for the education and training of technical designers and at a more fundamental level, their basic skills-set. It is the fundamental requirement for an understanding of appropriate solutions that provides the link between automated design and the education and training of designers.

The paper does not argue that there are inherent deficiencies in computerised design but that there are differences between computerised and manual design than need be recognised, understood and managed. The effects of computerisation is so profound that the high-level numerical skills of engineering designers are now largely redundant but there is an even greater need for a deep understanding of behaviour and a "feel" for appropriate solutions. The paper concludes that the education and training of designers will have to change to reflect the new demands of the computerised design environment.

KEYWORDS: automation, computerised design, de-skilling, education, IT, process integration, training, skills.

1. INTRODUCTION

This paper investigates the effect of automation of construction design processes using the computer. Traditional automation concentrates on physical processes using machines and more recently robots, but design processes use intellectual rather than physical skills and these have been far harder to automate until the invention of the digital computer. As much engineering design comprises of mathematical modelling, and the computer is highly efficient at executing mathematical computation, it is clear that there is now scope for significant efficiency gains and/or automation.

For the purposes of this paper automation is taken to mean the computerisation of any design process that was previously executed manually, especially when separate operations are integrated into a single seamless process.
Engineering design professionals are uncomfortable about the notion of automatic design, although efficiency of the process has become an established goal. It is the notion of a

machine automatically processing design information, without manual intervention, that seems to cause most consternation. Early software tools concentrated on specific aspects of design, and although they produced dramatic efficiency gains, this was not seen as "automatic" design. The current phase of engineering design software development has two facets that have changed this. The first is the ability of previously discrete packages to pass information automatically between each other. The second is the development and growing use of central 3D models. On their own, these developments are significant, together they are encouraging the total integration of all design disciplines (and construction and maintenance), which in turn facilitates automation.

The issues discussed in this paper apply to all technical design, but the author's experience in this area is based on structural engineering.

2. THE INFLUENCE OF COMPUTERS

Computers execute calculations at the touch of a button and much of construction design revolves around mathematical modelling and Computer Aided Draughting (CAD) which makes design processes an ideal candidate for automation.

Software is now so advanced that it effectively holds much of the detailed engineering knowledge (although critically not judgement). This can lead to the false assumption that the computer holds engineering expertise. The operator no longer needs to understand engineering processes or computation to obtain a solution.

The relative ease of producing calculations also encourages complexity, either in situations where a more straightforward design would suffice, or where the computational capability enables us to design more advanced system. In both cases this complexity may mask, or even encourage, error.

It is becoming increasingly difficult for younger engineers to develop the intuitive “feel” for technical design solutions and behaviour that their predecessors developed while producing manual calculations. It is this expertise that guides designers, and alerts them to inappropriate solutions.

There is also evidence to suggest that in some cases the power of the software is encouraging those with inadequate training or knowledge to engage in analysis and design, and in others that over-reliance is being placed in computer generated output. A combination of these factors can make error more likely and its detection more difficult. This risk needs to be recognised and managed.

3. DESIGN PROCESS AUTOMATION

Construction design can be broken down into various functions, most of which are ideally suited to computerisation. Technical design usually starts with a conceptual phase where real-world problems are analysed and idealised. This is a high-level skill, based on experience and although some software tools can assist, such as those based on artificial intelligence, this phase is not well suited to computerisation. When the real-world problem is broken down into discreet elements that can be modelled: analysis, design, drawing, detailing, scheduling and even planning, can be computerised. Once these processes are in an electronic form, partial automation has been achieved. When the software passes the output from one phase to another, full automation has arrived.

Although not strictly automation, another factor that is aiding the computerisation and integration of construction design is the development of full 3D building models. Additionally the recent innovation of centrally held and managed models, often utilising extranets or construction portals, will inevitably encourage electronic integration of design processes (and probably the organisational integration of traditionally separate design functions), that in turn will encourage further automation.

3.1 The benefit

Computerisation brings substantial benefits in the form of savings in skilled labour, faster design, error reduction and the ability to enhance design to a level not possible before the computer. The often quoted benefit of computers providing "more time to think" is however naive, where the need for efficiency will override any altruistic benefit. Any necessary "thinking" will be done irrespective of efficiency levels - any unnecessary thinking will still be unnecessary, however efficient design becomes!

The effect of efficiency gains must not be underestimated. Computations of great complexity, that would have taken hours to execute by hand, can now be completed in seconds. As software integrates analysis, design, drafting and scheduling, output suitable for manufacture can be created by one operator, from a single set of initial data. This is a potentially dramatic benefit that parallels productivity gains from automating physical processes. As complex calculations are performed by highly educated (and thus well paid), personnel, the potential cost savings are high. As a direct consequence of this automation, the skills balance of designers will change, with a reduced emphasis on mathematical skills and a greater need for conceptual abilities and knowledge of the operation, and critically, the limitations of software packages.

Apart from the obvious economic benefit of efficiency, speed of computation has made it possible to perform multiple iterations of complex designs allowing optimisation of solutions that were simply not feasible in the past. The rapid exploration of various design options will lead to enhanced product performance (as well as a more economically honed solution). Also, computer modelling of complex problems has led to more imaginative and creative structures (eg large stadia and aesthetically pleasing bridges), and safer buildings (eg modelling of the spread of fire, and the prediction of crowd behaviour).

Computers also have a significant role to play in error reduction. One of the traditional sources of design error was within manual computation. Proven software will virtually eliminate this as a problem. Data entry errors will be reduced by software integration, so automation via computerisation should provide substantial benefits in terms of reduction of this type of error.

3.2 The cost of the benefit.

As with the automation of physical processes, the benefits can only be achieved by the investment of capital. In this case it necessitates investment in hardware, software, communications systems and critically, technical support. This changes the balance between variable and fixed capital costs, increasing the reliance on investment and equipment, and requires access to capital. In turn this increases susceptibility to changing work volumes that are notorious within the built environment sector. In effect, capital expenditure allows variable costs to be saved but with increased financial risk [Gardner].

Rather ironically this benefit is ephemeral to the firm making the capital investment, as any cost-benefit eventually passes to society via more competitive pricing (but the risks associated with capital structures are permanent).

3.3 The problems associated with automation

In addition to the revised capital structure and the increased level of technical complexity, automation changes the process to such an extent that the risk of error alters significantly.

The use of computers in engineering design has become widespread, but the computer is only a tool. It could therefore be argued that computers should not alter the risk of error. However the evidence suggests that computer-assisted design does fundamentally affect the design process and can increase or decrease the risk of error depending on the circumstances. The potential for increased risk is illustrated below with two examples of catastrophic collapses, which have been attributed to computer error.

The problems associated with computerised design, come from the potential for unanticipated or unrecognised consequences as the design gets ever more automated and/or complex. As individual packages get linked together and data is automatically transferred between them, the risk increases as an error gets perpetuated, and is less easy to detect.

Errors have always occurred, some of which have led to catastrophic failure. Also some errors that would have led to catastrophic events have been avoided by utilising computer-assisted design (ie errors that would have occurred in manual design have been avoided). It is also unlikely that the same type of error would occur within computer and manual design, reinforcing the argument that computer-assisted engineering (CAE) has changed the risk. Error will continue, what has changed is the type and cause of this error. This necessitates different mechanisms for error detection, and the management of risk.

3.3 Computer assisted error

There are thankfully few examples where the computer has had a significant hand in catastrophic error. However there are two well-known structural collapses that are attributed, at least in part, to computer-assisted design, which together dramatically illustrate the issue.

3.4.1 Hartford Stadium, Connecticut, USA

The Civic Centre in Hartford Connecticut, USA consisted of a 2.2 acre roof supported on only four columns. In 1978 when loaded with snow (but fortunately empty of spectators), it collapsed [Carper]. The complex roof was designed with considerable computer assistance and would have been virtually impossible to design manually.

The collapse was attributed to two factors: an eccentric joint was assumed to have no eccentricity, and a strut was assumed to be braced when in fact it was not. The strut that initiated the failure had a capacity of 9% of that assumed in the design. The actual working deflection was twice that estimated by the computer analysis. Despite a heavy snow load, the actual imposed loads at the time of collapse were well within the design limits [Levy and Salvadori].

It is reported that the structure exhibited signs of distress during construction (lack of fit of fabricated components) and in its subsequent operation (excessive deflection), but these warnings signs were ignored based on a false confidence in the computer-assisted design.

3.4.2 Sleipner Offshore Platform

Sleipner was an offshore oil structure constructed in Norway. In 1991 it suffered a catastrophic collapse. The computer analysis was complex, using finite element analysis. It is reported that an error in the generation of the finite element mesh gave a poor representation of the shear forces at a critical joint, which resulted in a 45% under-estimate of the shear force. The joint was also poorly detailed, exacerbating the problem. The combination of these two factors led to its failure and the subsequent loss of the whole structure [Foeroyvik].

3.5 Lessons from Hartford and Sleipner

Both structures were highly complex and relied on the computer for analysis. In the case of the Hartford Stadium, it could be argued that the availability of the computer had encouraged a more complex design, which exacerbated the problem. A simpler structure would have been easier to check with manual calculations. The construction of the Sleipner platform probably could not have been made significantly simpler and is a good example of the benefits of the computer's power being used to understand more sophisticated structures via complex analysis, but also illustrates the difficulty in checking this type of complex analysis. The problem here seems to be that the full implications of the design’s complexity and the software’s limitations had not been fully appreciated.

Both structures were represented by models that were not sufficiently representative of the actual structure to give reliable results. Interestingly, despite the magnitude of these errors, in both cases the collapse was attributed to a combination of factors, rather than a single error.

3.6 Other errors

There are other less dramatic documented problems resulting from error and there must be many other errors (of a lesser magnitude) that have gone undetected and/or unreported. However the literature does identify some significant cases that range from software and hardware errors, to seemingly obvious errors that appear to have initially gone unnoticed by engineers [Puri] [Kratky].

4. SAFER COMPUTING

This paper has presented two fairly dramatic well-documented structural collapses that are, at least in part, directly contributable to computers, and there are many more examples of error. This however this does not mean the computer is the villain of the piece, for two reasons. Firstly, the computer is programmed and operated by people, and however powerful, it is only another tool in the control of the designers. Secondly the computer has allowed us to design and construct far more complex buildings than were possible in the past.

The evidence suggests that most computer-generated errors come from deficiencies in the modelling process, or a lack of understanding of the limitations of the software, rather than the actual computation or errors in the software itself. This gives us the first clue to developing a strategy to address the issues.

The problem comes down to CAE having a tendency to divorce the computation from a deep human understanding of structural behaviour and a “feel” for the likely solution. This is exacerbated by the fact that CAE encourages structural complexity (some justified by the project and some not).

Many organisations have recognised this and have published guidelines for the safer use of computers in engineering calculations. These usually recommend a systematic approach to computer analysis that breaks the process into a numbers of stages, each with its own verification and validation procedures, and the management of the process by qualified and experienced personnel [ISE] [NAFEMS].

Ultimately it is the industry’s responsibility to ensure it uses computers in a safe and appropriate way. The future must lie in education and training, and controls that ensure only those with appropriate knowledge, training and experience have responsibility for design output.

5. EDUCATION AND TRAINING

Every error must eventually be attributed to people (rather that the computer), but the issue is far more complex than simply distributing blame. Some computer error is attributed to software faults but analysis of known errors suggests that it is far more common for errors to occur as a result of correct computation of an inappropriate model. This establishes a direct link between the education and experience of the computer operator and the likelihood of an error occurring.

There is evidence of a "black box" syndrome developing in relation to computer analysis, whereby false confidence is generated in the output just because it came from a computer. This appears to be the case with the Hartford Stadium failure, where the structure exhibited signs of distress that were discounted because "the design was executed by computer". This creates a paradoxical situation whereby it is relatively easy to generate an answer for a complex problem by computer (and difficult to do this manually), but the complexity of the analysis and/or the problem itself, requires greater experience to recognise problems with the computer output.

Computerisation which embeds design information in the program also allows software to be operated by less experienced staff.

It is widely accepted that engineers gradually develop "a feel" for appropriate solutions by grinding through manual calculations. In the computer age the necessity for manual calculations has all but disappeared, making it more difficult for the engineer to develop this feel. The dilemma is that computer design increases the importance of an intrinsic understanding behaviour but that this feel for an appropriate solution is now more difficult to obtain.

This problem is exacerbated when computers are used to design complex structures that are virtually outside the capabilities of manual computation. It is of course one of the great benefits of computers that they are enabling us to design ever more complex and imaginative structures, but a consequence of this situation is that errors are more likely to go undetected. Both of the structures cited in this paper are complex and almost certainly would have been built differently had computers not been available to assist with analysis.

This problem gets even more complex if it is concluded that the skill-set required for traditional manual design (highly mathematical) is different from that required for computerised design (conceptual, developing appropriate models and appreciating the likely solutions to a problem). Whereas engineers have traditionally required highly developed mathematical skills, needing "left brain" skills, it is argued by some, that developing an inherent feel for appropriate engineering solutions, and the ability to develop appropriate models (suitable for computer analysis), is a far more imaginative skill needing "right brain" attributes [Brohn]. If this argument is correct it will have radical implications for the selection and training of future design engineers, as more will need to be drawn from different sections of the population (it is generally thought that left and right brain attributes are a matter of birth rather than education and training).

Computerisation will also affect the design of technical courses. Most traditional engineering courses have high levels of mathematics, the need for which has been radically reduced. The emphasis will need to shift to modelling and interpretation of results, rather than the historical emphasis on mathematics and analysis.

The implications of automation are indeed dramatic!

6. CONCLUSIONS

Despite the obvious difference between design and physical processes, there are great parallels in relation to automation. Considerable economic and performance benefits can be realised by investing in technology that automates design. The benefits are quantitative in terms of faster and more efficient design, saving the higher cost of traditional manual design and qualitative in terms of design enhancement. Automation also increases financial risk, changes the required skills and alters the chance and type of possible error.

We are entering a phase where most engineering processes are at least partly computer-assisted and the integration of design processes is leading to further automation. It's critically important that the implications of these changes are fully understood

The cases of catastrophic failure described in this paper dramatically support the contention that computer assisted design can lead to significant error, which highlights a problem which needs to be recognised and managed. However errors will always occur and no error can ultimately be blamed on the computer. All error eventually links back to people.

Computer assisted design reduces the necessity for engineers to have high-level mathematical skills and the evidence suggests that the emphasis should now be on conceptual design, modelling and interpreting the output of computer programs, rather than having the skill to actually perform the computation (which computers do so effectively). It is also far more difficult to develop a feel for behaviour and likely solutions as a result of computer-executed design and the more complex buildings that computer design has made possible. It is argued by some authors that this fundamentally changes the required skill-set of designers and that these issues need to be fully reflected in the education and training of engineers. A combination of these effects will change the future manpower requirements for engineers.

It is the industry's responsibility to ensure that the undoubted benefits available from computers are achieved without an unacceptable change in the associated risk.

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