# CIRCLY and Mechanistic Pavement Design:
# The Past, Present and Towards the Future

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## ABSTRACT

It has been about 30 years since CIRCLY, originally a FORTRAN program for analyzing Layered Elastic Media subject to surface loads, was released by CSIRO.

This paper gives an overview of how CIRCLY has evolved over these 30 years – from the first mainframe version, to the current user-friendly Windows based, version 5.0 as the standard pavement design package used in 35 countries.

The development of CIRCLY has closely tracked the evolution of the Austroads mechanistic flexible pavement design procedure. CIRCLY is unique amongst commercial software as it handles cross-anisotropic properties as required by the Austroads procedure. CIRCLY also automates many requirements of the Austroads procedure such as sublayering of unbound granular layers. A unique Parametric Analysis feature can fine-tune layer thicknesses to minimize pavement costs.

The capabilities of the two special versions of CIRCLY are also discussed:

- APSDS (Airport Pavement Structural Design System) for airport pavements, used for airports world wide such as Frankfurt Airport and Amsterdam's Schipol Airport. Airbus Industrie has used it to design landing gears for new aircraft models, including the A380.
- HIPAVE (Heavy Industrial PAVEment) for pavements in intermodal container terminals such as the Crawford Street Freight Village in New Zealand.

Some predictions are made about the future of the mechanistic pavement design procedure.

## INTRODUCTION

CIRCLY started life as a FORTRAN program for analyzing Layered Elastic Media subject to surface loads (Wardle, 1977b). The acronym **CIRCLY** came about because at the time the CSIRO FORTRAN compiler had a limit of 6 characters for the program name (and any variable). **CIRC** was short for **CIRC**ular loads (i.e. circular contact area) and **LY** was an abbreviation for **L**a**Y**ered Systems.

CIRCLY calculates the load-induced stresses, strains and displacements at any nominated points in the layered system.

Cross-anisotropic material properties can also be considered as well as the usual isotropic properties. A cross-anisotropic material is assumed to have a vertical axis of symmetry. Anisotropies of this type have been observed in soil and rock deposits due to processes involved in their natural formation. In addition, compaction of pavement layers during construction always produces anisotropy. The interfaces between the layers can be either fully continuous (rough) or fully frictionless (smooth), or a combination of both types. From a practical standpoint the response of the actual pavement interfaces will be somewhere between these theoretical limits. The fully continuous case is always assumed for pavement design. A prototype version of CIRCLY has also been developed that can model partial interface failure. The degree of interface slip is defined via a user-specified shear spring compliance.

In addition to pavement design, CIRCLY is also used in foundation design and soil settlement analysis.

CIRCLY can consider a comprehensive range of load types, including vertical, horizontal, torsional, etc. The surface contact stresses can be non-uniform, specified in terms of a polynomial distribution.

This paper gives an overview of how CIRCLY has evolved over these 30 years – from the first mainframe version, to the current version, CIRCLY 5.0.

The development of CIRCLY in the last 20 years has been closely tied to the release and evolution of the Austroads mechanistic procedure for flexible pavement design. CIRCLY has had a symbiotic relationship with the Austroads Guide. CIRCLY is unique amongst commercially released layered software in that it can handle cross-anisotropic properties as required by the Austroads procedure. A unique Parametric Analysis feature can optimize the thicknesses of up to three layers, allowing layer thicknesses to be fine-tuned to minimize construction and maintenance costs.

CIRCLY was a “mainframe” program when first released by CSIRO. By the time CIRCLY was commercialized in 1988 by MINCAD Systems, powerful personal computers were widely available, making the mechanistic pavement design procedures readily accessible.

The first commercial Windows version, CIRCLY 3.0, was released in late 1996. This was the first version that comprehensively supported the Austroads Guide. Many requirements of the Austroads Guide were automated such as sublayering of unbound granular layers. Since then, each major version has increased the support for the Austroads Guide.

Firstly, in this paper, the origins of CIRCLY and the background to the numerical method are discussed. This is followed by an introduction to the mechanistic flexible pavement design methodology. The next sections trace the development of the CIRCLY package. Later sections introduce the two special versions of CIRCLY: APSDS (Airport Pavement Structural Design System) for airport pavements and HIPAVE (Heavy Industrial PAVEment) for pavements in industrial facilities such as intermodal container terminals. Another section introduces recent research directions, in particular the trend towards using load spectra to replace standard axles as the primary load input for mechanistic design.

Some predictions are made about the future of the mechanistic pavement design procedure.

## Numerical Method

The evolution of CIRCLY can be traced back to Charles Gerrard’s Ph.D. research in the late 1960s (Gerrard, 1969). This research was sponsored by the Australian Road Research Board. Charles Gerrard joined CSIRO Division of Soil Mechanics (soon to be Division of Geomechanics) in 1967. He continued pursuing his research interest in layered elastic systems along with W. Jill Harrison in 1968.

Leigh Wardle joined CSIRO in 1970 as a “Mathematical Programmer”. Much of Leigh’s work involved developing analytical elastic solutions (e.g. Gerrard and Wardle, 1973) and software development in the FORTRAN language. He developed the two forerunners of CIRCLY: CRANLAY and UCRANLAY (Harrison et al., 1972). These two programs handled different circular loadings, and over the next few years the capabilities of these programs were merged into CIRCLY.

CIRCLY is based on integral transform techniques and offers significant advantages over other linear elastic analysis techniques such as the finite element method. Input data for the program is much simpler than that required for most finite element programs.

The analytical solutions for the stresses, strains and displacements are given by integral transform methods (Wardle, 1977a). The solutions involve integrals of the form:

$$I = \int_0^\infty A(k)\ J_\eta(k)\ J_\tau(kr)\ \exp(\pm\delta kz)\ k^\mu\ dk$$

where J denotes the Bessel function of the first kind, and r and z are expressed as multiples of the loaded radius. The coefficients A(k) are found by solving a set of simultaneous equations which represent the loading conditions at the surface, the interface conditions between the layers, and the conditions at the base of the lowest layer. The integrals are evaluated numerically.

## MECHANISTIC PAVEMENT DESIGN

The evolution of CIRCLY has been intimately linked to the development of the Austroads flexible pavement design method.

CIRCLY was officially adopted for flexible pavement design in Australia with the publication in 1987 of *Pavement Design – A Guide to the Structural Design of Road Pavements* by the National Association of Australian State Road Authorities (NAASRA), the (then) umbrella organisation of the Australian State Road Authorities (SRAs). The Pavement Design Guide has subsequently undergone major revisions by Austroads in 1992, 2004 and 2008. See Austroads (2008b) for the full background to the development of the mechanistic approach.

Many people have been involved in the evolution of the Guide into the present version - the “fathers” of the Guide could fairly be claimed to be the Drafting Committee for the 1987 Guide. These are:

- Mr David Potter (Convener), Australian Road Research Board
- Dr Gavin Donald, Department of Main Roads, NSW
- Mr Geoffrey Youdale, Department of Main Roads, NSW
- Mr David Anderson, Road Construction Authority, Victoria
- Dr Ron Gordon, Main Roads Department, Queensland

The publication of the 1987 Guide was a major step forward in road pavement design in Australia. For the first time, the Guide provided a comprehensive mechanistic approach to flexible pavement design using a mathematical model with inputs of engineering properties and outputs derived from material performance data.

Prior to this pavement design was empirically based. This had worked well since the 1950s as most pavements consisted of unbound granular materials with a sprayed seal or, in some cases, a thin asphalt wearing surface.

The advantages of the mechanistic approach, compared to an empirical procedure are:-

- the ability to take into account many more variables and test these for sensitivity
- the ability to rationally assess the likely performance of novel materials and loading conditions

The 1980s saw the widespread availability of powerful personal computers ensuring that the mechanistic pavement design procedures would be readily accessible.

Briefly, the Austroads flexible pavement design method uses CIRCLY to calculate load-induced elastic stresses, strains and deflections in model pavements. Figure 1 shows the mechanistic pavement model. The surface loading is the “standard axle”. Two critical strain components are used to design pavements. The maximum vertical compressive strain at the top of the subgrade is related to the repetitions to cause surface rutting failure. The maximum horizontal tensile strain at the underside of the asphalt or cemented layers is related to repetitions to cause fatigue cracking of those layers.

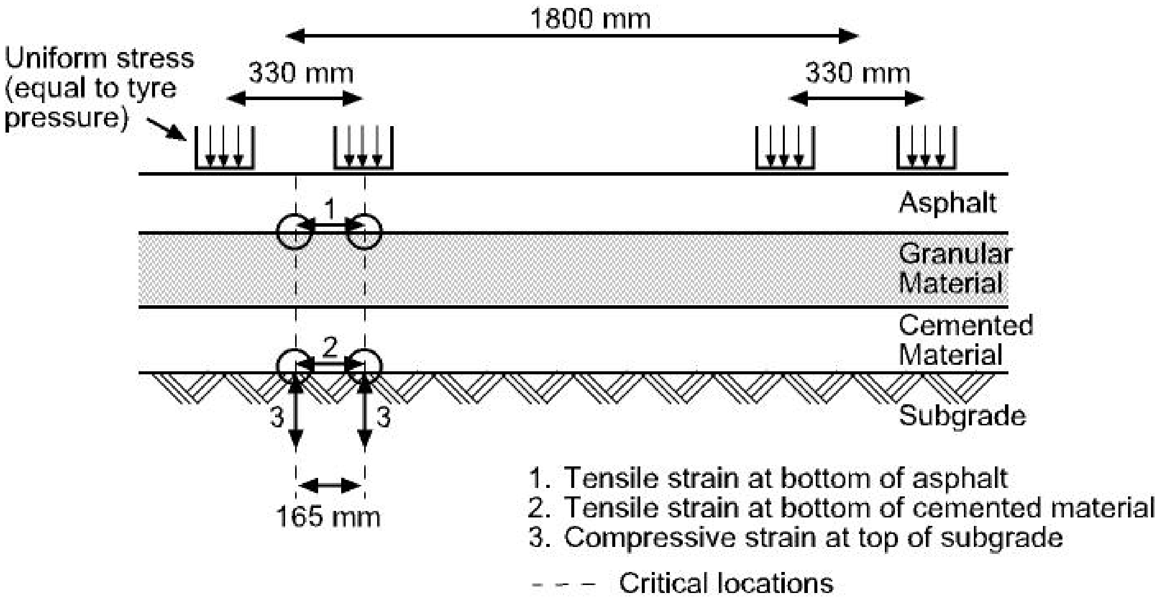

***Figure 1: Pavement Model for Mechanistic Procedure***

The 'mechanistic' design method involves calculating pavement damage from these critical strains using empirical equations called 'failure criteria' or 'performance relationships' of the form:

$$N = \left[\frac{k}{\varepsilon}\right]^{b} \qquad (1)$$

where $N$ is the predicted life (repetitions of $\varepsilon$)

$k$ is a material constant.

$b$ is the damage exponent of the material.

$\varepsilon$ is the load-induced strain

The empirical parameters $k$ and $b$ are determined by calibrating the design method against observed performance of test pavements or of pavements in service.

## Cumulative Damage Factor and Miner's Hypothesis

Although the Austroads flexible pavement design method does not mention the Cumulative Damage Factor (CDF) concept, it has been adopted in CIRCLY as the primary means of presenting results both numerically and graphically.

The standard axle approach used for mechanistic highway pavement design is primarily a consequence of the empirical performance data resulting from mixed traffic loading. For pavement design projects involving very heavy loads imposed by large aircraft or container handling vehicles, it is not appropriate to use any sort of "equivalent" axle or wheel. For these projects the actual wheel configurations and loads of all vehicles in the design mix should be specified.

The CDF concept is then needed to predict the total damage. This treats the level of pavement strain response to vehicle loading as a direct indicator of pavement damage over the complete life of the pavement. The cumulative damage from all of the vehicles contributes to the failure of the pavement according to the strain imposed by the individual vehicles.

The Damage Factor for the i-th loading is defined as the number of repetitions ($n_i$) of a given strain divided by the 'allowable' repetitions ($N_i$) of the strain that would cause failure. The

Cumulative Damage Factor is obtained by summing the damage factors over all the loadings in the traffic spectrum using Miner's hypothesis.

The Total Damage Factor is defined by:

$$CDF_{Total} = \sum_{i=1}^{LoadCases} CDF_i \qquad (2)$$

i is summed over the mix of loads, for example, different container vehicles.

The pavement is presumed to have reached its design life when the cumulative damage reaches 1.0. If the CDF is less than 1.0, the pavement has excess capacity and the CDF represents the proportion of pavement life consumed by the design traffic. Conversely, if the CDF exceeds 1.0 then the pavement is deemed to be unacceptable and must be modified in the next trial so that the deficiency is overcome. For example, this might mean an increase in pavement thickness or a modification to stiffness. The process is repeated until a satisfactory result in achieved.

## Anisotropic Material Characterisation

Isotropic materials have the same properties in all directions, whereas anisotropic materials do not. The cross-anisotropic case has an axis of symmetry of rotation. The properties are assumed to be equal in all directions perpendicular to this axis, but different to those in the direction of the axis. Assuming the axis of symmetry to be vertical, the five parameters required are $E_v$, $E_h$, $F_v$, $\nu_h$ and $\nu_{vh}$.

The original NAASRA working group had noted that measured deflection bowls were narrower than those estimated from elastic layer analysis using isotropic models. The view was taken by the working group that anisotropic models were appropriate for modelling granular and subgrade materials – as a surrogate for the actual stress-dependence of "modulus".

To obtain a closer fit between observed and CIRCLY-estimated deflection bowls, a value of 2 for the modular ratio ($E_v/E_h$) was adopted for both granular and subgrade materials as a 'best estimate'. The values of $\nu_h$ and $\nu_{vh}$ were taken to be the value of the isotropic $\nu$. The remaining cross-anisotropic parameter – $F_v$ – was set equal to $E_v/(1+\nu)$.

With these additional assumptions, the cross-anisotropic characterisation of granular and subgrade materials was specified by values for $E_v$ and $\nu$. Isotropic properties were considered to be appropriate for asphalt and cemented materials.

## Unbound granular materials

Unbound granular pavement materials such as graded crushed rock basecourse and natural gravels require special attention because their elastic stiffness depends upon the stress state at each point in the material. The layered elastic method cannot fully deal with stress dependence. This is because of the important limitation of the method that elastic moduli must be constant within each horizontal layer. Stress diminishes with distance from the wheels so the modulus will also change with distance from the wheels, both in the horizontal and vertical directions.

However, the layered elastic method can take stress-dependence into account to some degree by dividing granular layers into sublayers and assigning moduli to each sublayer. This allows the modulus to change with depth. CIRCLY automatically subdivides granular layers and assigns moduli in accordance with the method specified in the Austroads Guide. Previously this was carried out manually by the designer.

## CIRCLY – moving from mainframe to Personal Computer

When first released by CSIRO, CIRCLY 1.0 was a “mainframe” program. It was originally distributed in the form of the FORTRAN source code on industry standard magnetic tape.

CIRCLY 2.0 was released in November 1976.

CIRCLY was originally written to compile with the FORTRAN IV compilers used on the Control Data Cyber series computers that were operated by CSIRO. Recipient organizations with operating systems and computers from other manufacturers often had problems getting CIRCLY to compile and execute. This issue was overcome in early 1986 with the release of CIRCLY conforming to the ANSI FORTRAN 77 Standard.

In all, about 40 mainframe CIRCLY licences were distributed – mostly to Universities, State Road Authorities, large consultants, asphalt suppliers etc. During that era CIRCLY was out of the reach of small and medium organizations due to the computer resources required.

The big breakthrough was the release of the first IBM PC version in March 1986. This put CIRCLY within the reach of all those with access to a personal computer. Because the “ready to run” executable software was distributed as a binary file on 5.25 inch floppy disk it could be run on any PC running the popular MS-DOS operating system. At that time CIRCLY did not have any sort of user friendly “front end” program. Input data and result files could only be accessed with a text editor.

Leigh Wardle left CSIRO in early 1988 to start Mincad Systems with CSIRO colleague, Ken McNabb. CIRCLY was commercialized in 1988 by Mincad Systems under a 3 year licence agreement with CSIRO. In 1988 the first CIRCLY “package” was released. For the first time this included a “front end” program for data input and for viewing numerical results. Mincad Systems purchased the full CIRCLY intellectual property from CSIRO in 1991.

## CIRCLY 3.0

CIRCLY 3.0, the first Microsoft Windows version was released in late 1996.

CIRCLY 3.0 included many improvements and was the first version of CIRCLY that addressed the Austroads pavement design method. For example, it could automatically generate sub-layers for granular materials. It also presented numerical results in the form of graphs of the Cumulative Damage Factor for any nominated layer. Microsoft Excel macros were used to generate the graphs.

## CIRCLY 4.0

CIRCLY 4.0 was released in early 1999. A major new feature was the automatic thickness design capability. This feature would automatically determine the required thickness of any chosen layer to produce a pavement that caters for the design traffic without overstressing any layer. CIRCLY 4.0 introduced a comprehensive range of graphs (using MS Excel). The CDF for any layer could be plotted along the transverse axis *(*Figure 2*).* Other graphs could be generated for any user-nominated component (strains, stresses, deflections, etc.) at selected depths below the surface, in either two or three dimensions (Figure 3 and Figure 4).

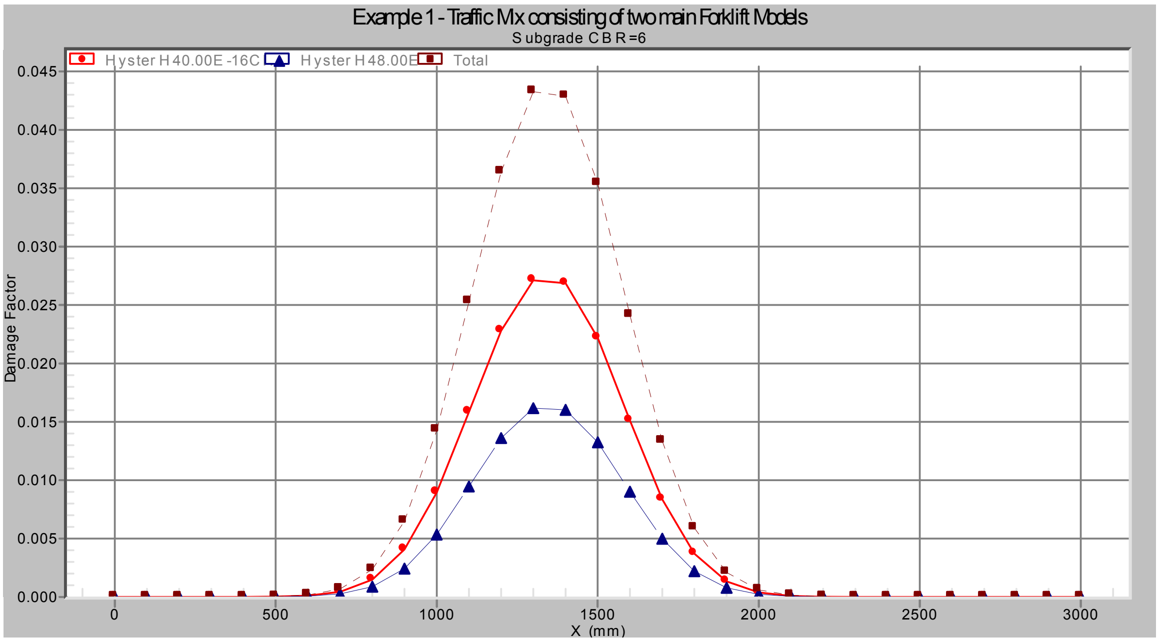

*Figure 2: Sample Cumulative Damage Factor graph*

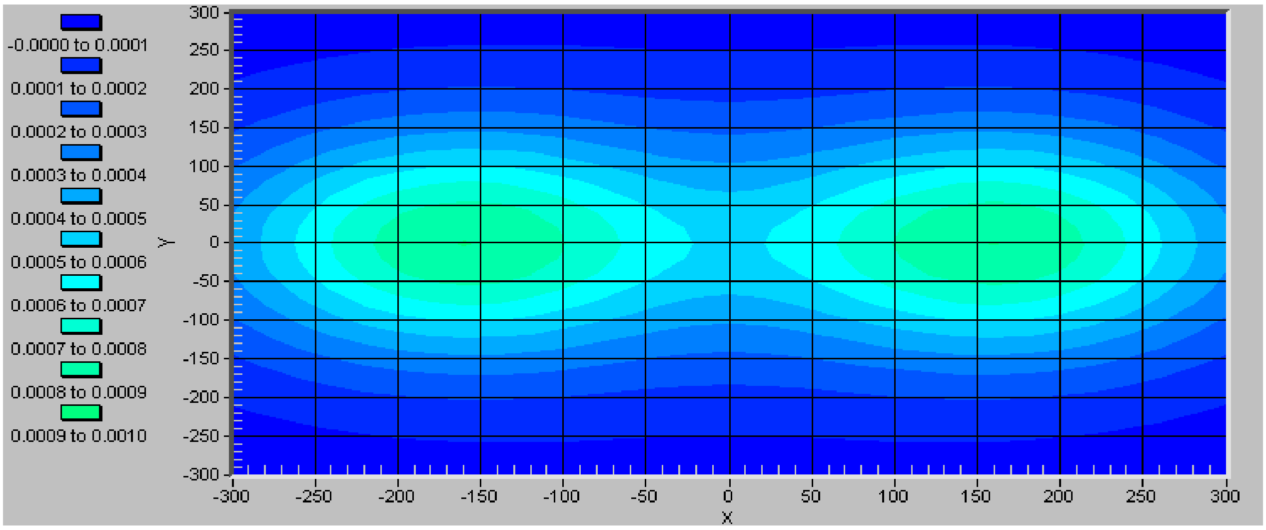

*Figure 3: Sample 2-dimensional contour plot of strain*

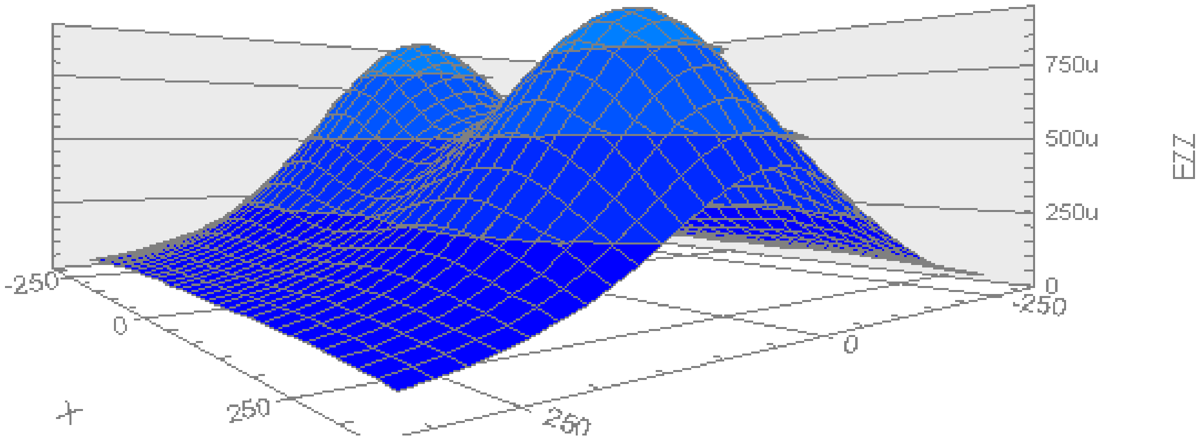

***Figure 4: Sample 3-dimensional plot of strain***

## CIRCLY 5.0

CIRCLY 5.0 was released in early 2004. The primary catalyst for CIRCLY 5.0 was the impending release of the 2004 Austroads Pavement Design Guide. The new Guide impacted on the use of CIRCLY in a number of areas, such as the change to the 4 wheeled Standard Axle and new methods for sublayering granular materials.

CIRCLY 5.0 introduced some very powerful features that facilitate cost optimization.

## Cost Optimization / Automatic Parametric Analysis

CIRCLY 5.0's Automatic Parametric Analysis feature automatically loops through a range of thicknesses for one or two nominated layers. By combining Automatic Parametric Analysis with the Cost Analysis feature layer thicknesses can be fine-tuned to minimize construction cost.

The following Case Study illustrates these concepts. Figure 5 shows the pavement structure and assumed unit costs. The thickness of the wearing course asphalt is assumed to be fixed at 40 mm. The thicknesses of the 2nd and 3rd layers are treated as unknowns.

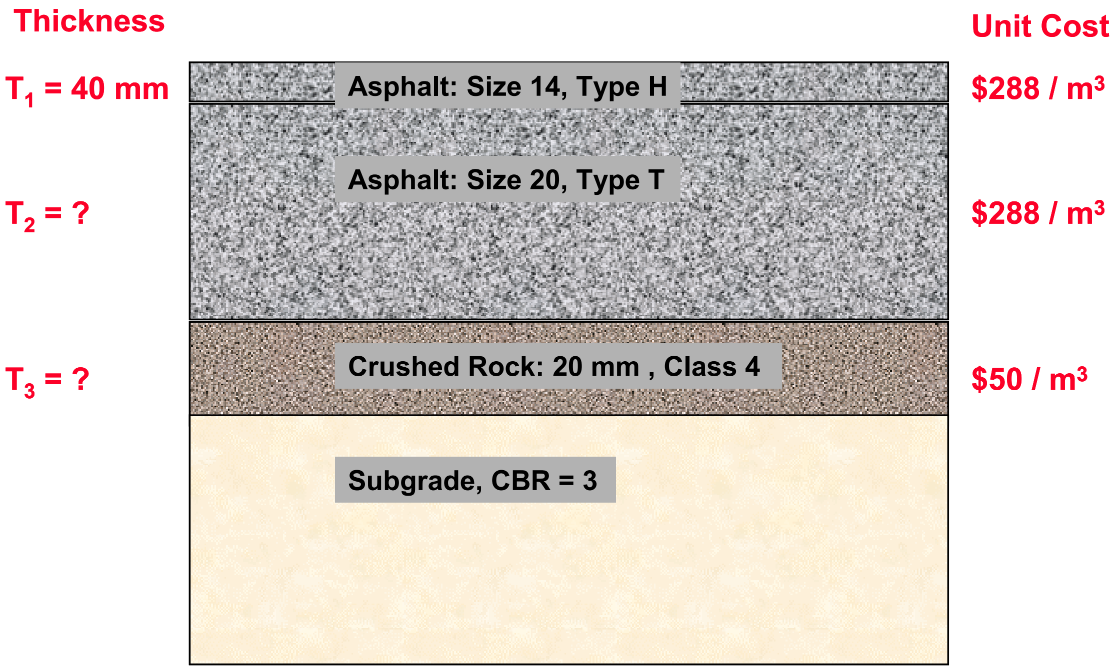

***Figure 5: Pavement structure used for Parametric Analysis + Cost Analysis Case Study***

The Automatic Parametric Analysis feature is used to automatically loop through a range of thicknesses for one layer (Layer 2) and to determine which thickness has the minimum Total Cost. For each Layer 2 thickness, CIRCLY automatically designs the thickness of Layer 3.

Table 1 summarizes the results.

Here Layer 3 is constrained to a minimum constructible thickness of 100 mm. This constraint is activated when the thickness of Layer 2 is 220 mm or less resulting in the maximum CDF being less than 1.0.

***Table 1: Summary of results for Cost Analysis Case Study***

| **Layer 2 Thickness (mm)** | **Layer 3 Thickness (mm)** | **Maximum CDF of all layers** | **Total Cost ($\$/m^2$)** |
|---|---|---|---|
| 170 | 1826 | 1.0 | 151.7 |
| 180 | 973 | 1.0 | 112.0 |
| 190 | 573 | 1.0 | 94.8 |
| 200 | 343 | 1.0 | 86.2 |
| 210 | 189 | 1.0 | 81.4 |
| 220 | 100 | 0.89 | 79.9 |

Figure 6 shows the automatically generated graph of Total Cost vs. Layer 3 Thickness.

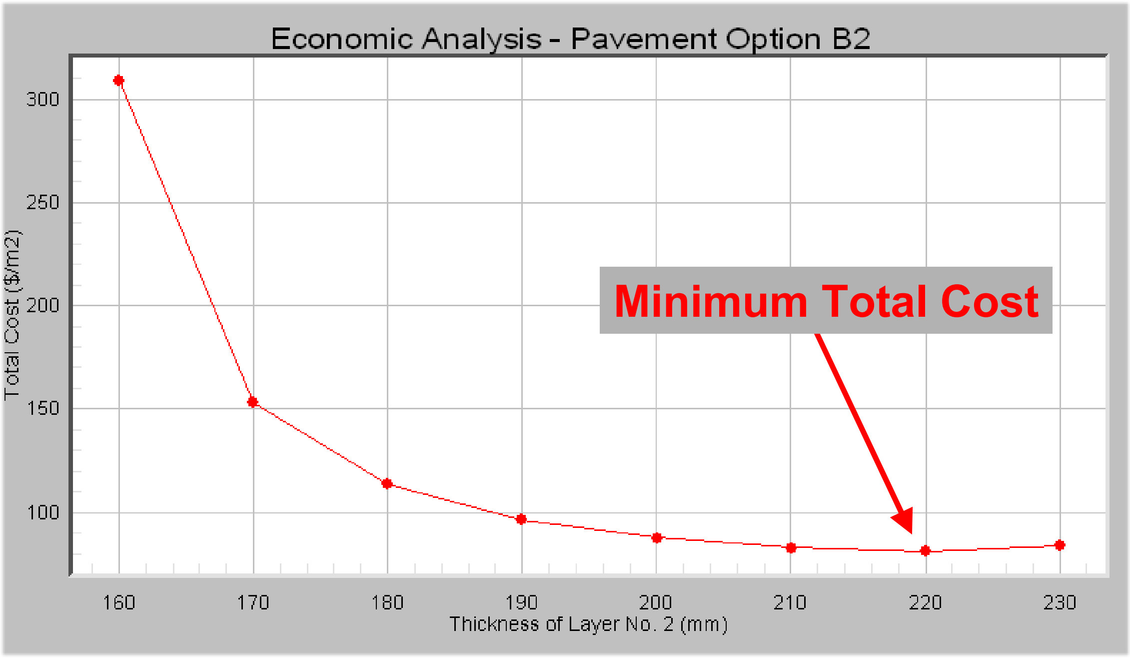

***Figure 6:  Automatically generated graph: Total Cost vs. Layer 3 Thickness***

The Case Study illustrates the important point that although every one of the 6 alternative pavement designs is valid according to the Austroads method, the cost variation is almost a factor of 2.

## AIRPORT PAVEMENT STRUCTURAL DESIGN SYSTEM (APSDS)

In mid-1993 Ian Rickards of Pioneer Road Services of Australia was developing an improved method for incorporating lateral vehicle wander of aircraft into the damage calculation.  He utilized a Lotus 123 spreadsheet that used CIRCLY for calculating the critical strains.  Pioneer Road Services subsequently financed the development of a prototype version of the CIRCLY engine that efficiently integrated lateral vehicle wander into the damage calculation algorithm.  The original concept was described by Monismith et al. (1987) but could not be implemented at that time because the computations could not be performed quickly enough for regular design use.  The total damage at any point includes contributions from all the wheels in all their wandering positions.  This contrasts with conventional mechanistic design procedures, including that of Austroads, in which only single maximum values of  strain are used to estimate pavement life.

The “wander-capable” version of the CIRCLY engine formed the basis of the Airport Pavement Structural Design System (APSDS) - subsequently developed by Ian Rickards and Leigh Wardle.  The initial development of the system was financed by Pioneer Road Services.  The theory and background to APSDS is given by Wardle and Rodway (1995) and Wardle et al. (2001).

The first commercial version, APSDS 3.0, was released in late 1996.  APSDS 4.0 was released in mid 2000 and extended the software to include an automatic thickness design capability.

One of the challenges in advancing APSDS for pavement design was that initially there were no existing performance relationships that could be used to predict subgrade damage.  This was a consequence of the unique algorithm used to calculate damage taking account of wander.

A number of versions of the APSDS-specific subgrade performance calibrations have been developed, the most recent being Wardle and Rodway (2010).

For all these calibrations the Barker-Brabston method has been used for sublayering the unbound granular materials (Barker and Brabston, 1975).  The Barker-Brabston model and the derived subgrade damage models assume the granular layers to be isotropic.

APSDS is now a mature product and has been used for major international projects such as the 5th runway at Amsterdam's Schipol Airport and the northern runway at Frankfurt Airport. It was also used by leading aircraft manufacturer *Airbus* to design landing gear configurations for their latest aircraft models, including the A380.

APSDS 5.0 is planned for release in the second half of 2010. In addition to the usual graphs of damage versus distance, APSDS 5.0 generates spectral damage graphs as shown on Figure 7. These show, for the critical point on the pavement, the damage contributions from each aircraft as the aircrafts' weights increase. APSDS 5.0 includes CIRCLY 5.0's advanced features such as the Parametric Analysis and Cost Analysis features. APSDS 5.0 implements the 'reservoir' method, as used in bridge design to handle complex loadings, to consistently calculate the damage from overlapping strain pulses due to multi-axle landing gears. Earlier APSDS versions could only calculate damage based on the following two extremes:

- multiple distinct short pulses resulting from each axle, for shallow depths
- a single longer pulse that reflects the overall loading on the gear, for large depths

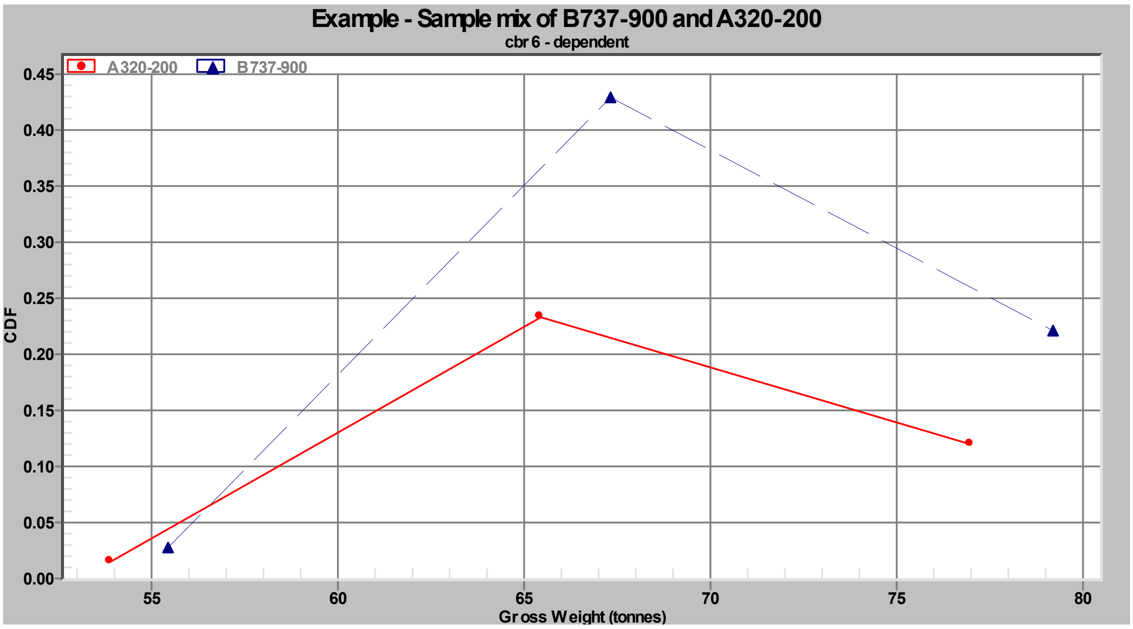

*Figure 7: APSDS 5.0 spectral damage graph*

## HIPAVE

While CIRCLY and APSDS have been used very successfully for the design of heavy duty industrial pavements, unwieldy data input makes it very difficult to model more than a few different vehicle models or payloads per vehicle. HIPAVE 5.0 (**H**eavy **I**ndustrial **PAVE**ment design) was designed from the ground up to conveniently handle the comprehensive details of the freight handling vehicles and the characteristics of the payload distribution for each vehicle (Wardle et al., 2006).

HIPAVE 5.0 was released in late 2005 and has been used on many projects, for example the. Crawford Street Freight Village in New Zealand.

The unique features of HIPAVE are:

- a standard vehicle library - that can be automatically updated via the Internet;
- ability to define and store container weight distributions;
- automatic calculation of axle loads from vehicle geometry and container weight;

- full spectral analysis of pavement damage by using the cumulative damage concept to sum the damage from multiple vehicle models and payloads.

HIPAVE combines features of both CIRCLY and APSDS. HIPAVE 5.0 includes the advanced features that were first introduced in CIRCLY 5.0, such as the Parametric Analysis and Cost Analysis features. HIPAVE 5.0 also includes lateral vehicle wander.

HIPAVE allows analyses to be conducted by directly using a mix of vehicle models. It is not necessary to approximate passes of different vehicles or axles to passes of an “equivalent” standard load or "design vehicle"; the specific details of the actual vehicles can be used.

Figure 8 is a sample cumulative damage plot produced by HIPAVE:

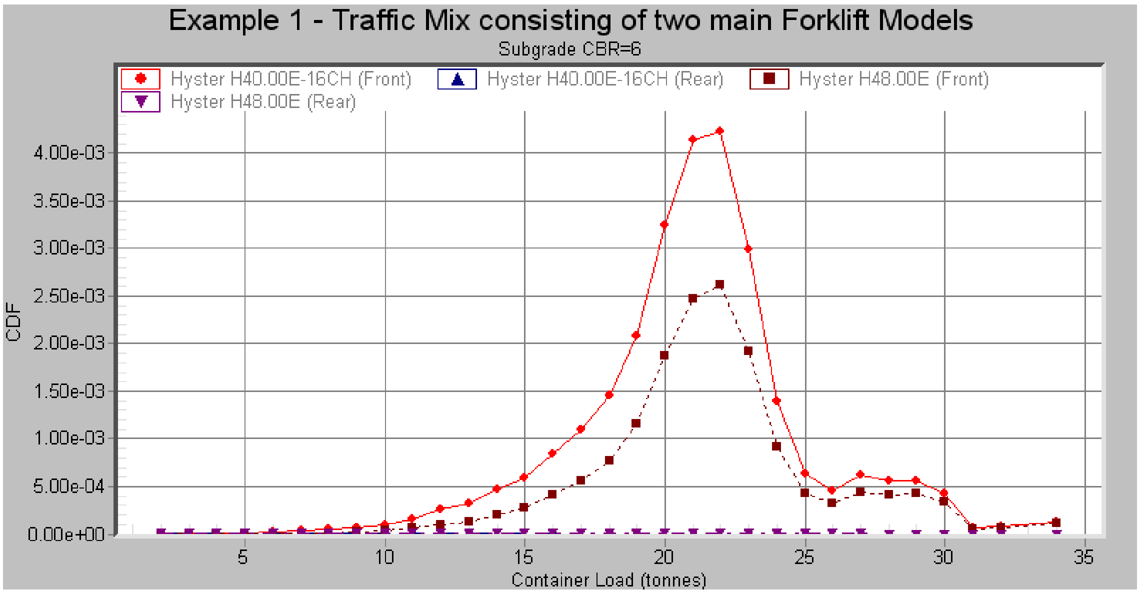

*Figure 8: HIPAVE graph - Subgrade Damage Factor vs. container load.*

HIPAVE can also generate graphs that show the variation of the damage factor across the pavement.

## Heavy Duty Industrial Pavement Design Guide

Many aspects of the design methods for highway/road pavements such as those presented in the Austroads Guide, are not appropriate for designing heavy duty flexible pavements for applications such as ports and container terminals. In particular, the empirical pavement performance relationships that are used for road design should not be used to design pavements that carry much higher loads. The only available performance relationships for very large wheel loads are those developed from full-scale tests on aircraft pavements. These are used by HIPAVE.

Traditionally, port pavements have been designed using chart-based, empirical processes such as the British Ports Association method (British Ports Association, 1986, 1996). In the early 2000s the ASCE started developing a Port and Intermodal Yard Pavement Design Guide. Smallridge and Jacob (2001) give an outline of the Guide, but the full Guide has not been published.

In 2006 Leigh Wardle and Ian Rickards (Pioneer Road Services) commenced development of the **Heavy Duty Industrial Pavement Design Guide**, targeted at users of the HIPAVE software. The Guide was released in March 2007 (Mincad Systems/Pioneer Road Services, 2007). The Guide is a collaborative effort also involving John Lancaster (formerly Pioneer Road Services, now VicRoads) and Dr. Susan Tighe (Dept. Civil Engineering, University of Waterloo, Canada). The Guide outlines best practice in the design of new construction and rehabilitation of industrial pavements. It steers the designer through key design considerations and suggests external sources for research updates. It is a ‘living document’ that will be updated to reflect advances in pavement technology and made freely available via the Internet at no charge from www.mincad.com.au/hdipdg/ .

# FUTURE DIRECTIONS

This section introduces recent research directions, in particular the trend towards using load spectra to replace standard axles as the primary load input for mechanistic design.

## Load Spectral Analysis vs. Standard Axles

Internationally, there is a trend towards using load spectra to replace standard axles as the primary load input into mechanistic design. The standard axle is an artefact of the “pre-computer” era – it was necessary to use it to simplify hand calculations so that simple thickness design charts could be used. Furthermore, the standard axle approach inherently involves loss of information due to the very crude assumptions made about “equivalent” damage for different loads and axle groups. Another limitation is that only one set of parameters is used to define material properties of the pavement layers. However, it is well established that pavement material properties significantly change with prevailing climate. For example, asphalt modulus is heavily dependent on the temperature, and the modulus of unbound granular materials depends on the moisture content.

The U.S. National Cooperative Highway Research Program (NCHRP) has developed the Mechanistic-Empirical Pavement Design Guide (MEPDG) (NCHRP, 2002). The MEPDG flexible pavement design procedure uses a layered elastic analysis. The procedure offers improved traffic characterization by direct modelling of axle load distributions and configurations. The detail can include hourly load distributions. Material properties can vary seasonally right down to the hourly level. Like APSDS and HIPAVE, the MEPDG procedure takes account of lateral vehicle wander.

In 2004 a prototype version of HIPAVE was created with unique features for detailed modelling of traffic load spectra (Wardle and Cropley, 2004). This version allowed individual combinations of axle group configurations and loads to be explicitly modelled. Figure 9 shows the damage contributions from each axle group considered, i.e.:

- single axle with single tyres (SAST),
- single axle with dual tyres (SADT),
- tandem axle with dual tyres (TADT),
- tridem axle with dual tyres (TRDT)

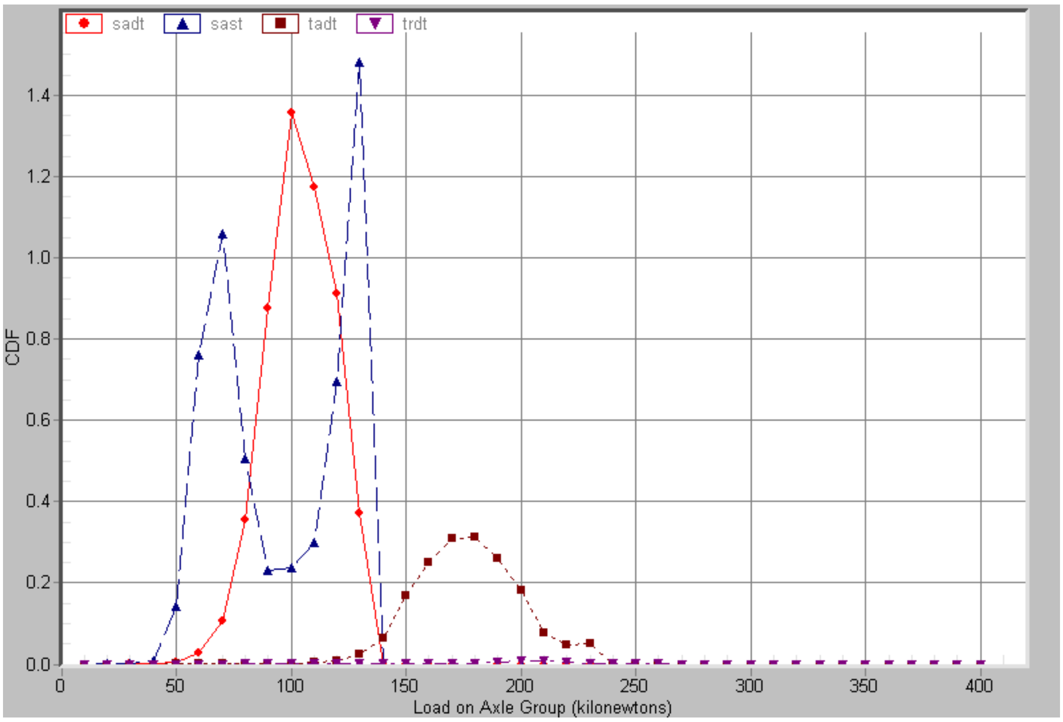

***Figure 9: Sample Damage Factor Graph – Highway Pavement Load Spectra Analysis using HIPAVE***

Research at Monash University has explored strategies for incorporating climatic conditions in mechanistic pavement design (Lee, et al., 2007). The traffic load spectra measured at existing Culway (weigh-in-motion) stations are directly analysed in CIRCLY, bypassing the use of standard axle loading. The pavement deterioration is modelled continuously taking into account the actual traffic load spectra and time dependent material properties.

It is expected that research along these lines can lead to more rational design methodologies for pavement design.

## Modelling tyre-pavement contact stress

Most pavement design methodologies such as Austroads assume the tyre-pavement contact stress is equal to the tyre inflation pressure and uniformly distributed over a circular contact area. However, the tyre-pavement contact area is not in a circular shape and the contact stress is neither uniform nor equal to the tyre inflation pressure. CIRCLY has been used to consider the effect of modelling measured 3-D contact stresses on pavement response (Luo and Prozzi, 2005, 2007). These studies showed that the uniform stress model underestimates the longitudinal strains under a combination of thin surface layer and low tyre pressure, and underestimates the transverse strains under a combination of thin surfacing, low tyre pressure and high wheel loading.

## Back analysis of weigh-in-motion data

There is considerable potential to develop new performance relationships by back analysing traffic load spectra measured at existing weigh-in-motion (WIM) stations. For example, Vicroads has an extensive database on the long term performance of heavily trafficked pavements (Papacostas and Bowman, 2003).

The proposed approach would entail modelling the load spectra directly in CIRCLY. The parameters k and b used in the subgrade performance model (see Equation 1) would be treated as unknowns and determined by the least squares goodness of fit between the observed pavement lives and model lives.

# CONCLUSIONS

From CIRCLY's origins as a layered elastic "numerical engine" on mainframes it has developed into a powerful, user friendly Windows based system for flexible pavement design. It specifically addresses the needs of designers working with the current Austroads design method.

Special versions, APSDS and HIPAVE, have been developed for the more challenging needs of airport pavement designers and designers of pavements for other heavy duty projects such as container terminals and other industrial facilities. These packages do a full spectral analysis of pavement damage by using the cumulative damage concept to sum the damage from multiple vehicle models and loadings. Both packages rigorously incorporate lateral vehicle wander.

CIRCLY, APSDS and HIPAVE do not impose a 'black box' approach to pavement design. The user can specify all design inputs, including material properties, each material's performance relationship and any wheel loading configurations. This flexibility and transparency gives the experienced designer easy access to, and control of, the full capabilities of a layered elastic 'mechanistic' method.

The program's computational speed (typical runs take seconds on current PCs) and easily changed problem inputs (wheel loads and spacings, tyre pressures, repetitions, pavement layer thicknesses, material properties, performance relationships) allow the designer to assess the sensitivity of the design to any input or design assumption.

Use of performance relationships that have been developed for roads can lead to grossly under-designed pavements. The only available performance relationships for very large wheel loads such as encountered on airports and container terminals are those developed from full-scale tests on aircraft pavements. These are used by HIPAVE. The **Heavy Duty Industrial Pavement Design Guide** represents best practice in the design of new construction and rehabilitation of industrial pavements. The Guide will evolve to reflect new research, particularly data from the U.S. National Airport Pavement Test Facility (NAPTF).

For highway pavements, new design procedures are being developed that use load spectra as the primary load input. This approach can take account of material properties that change with prevailing climate. The U.S. Mechanistic-Empirical Pavement Design Guide may be overly complicated for Australian conditions, but some features such as load spectra details and lateral vehicle wander could be readily adopted in Australia and New Zealand.

Although inelastic approaches such as the finite element method have the potential to provide more accurate predictions, the downside is the increased numbers of input parameters. The major challenge is to calibrate the models - this can require orders of magnitude more effort than for simple linear elastic models. There is clearly more value in predictions from a well-calibrated simple model, than from an inadequately calibrated complex model with unknown or poorly characterized reliability.

CIRCLY versions have been extended to handle conditions and design requirements beyond the simple requirements of the basic mechanistic pavement design methodology. The program's speed and ease of use facilitate optimum pavement designs and minimise costs.

The fundamental principles and concepts underlying the CIRCLY program continue to be as relevant today as they were 30 years ago. The CIRCLY "family" will continue to be enhanced to handle emerging design approaches as they evolve.

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