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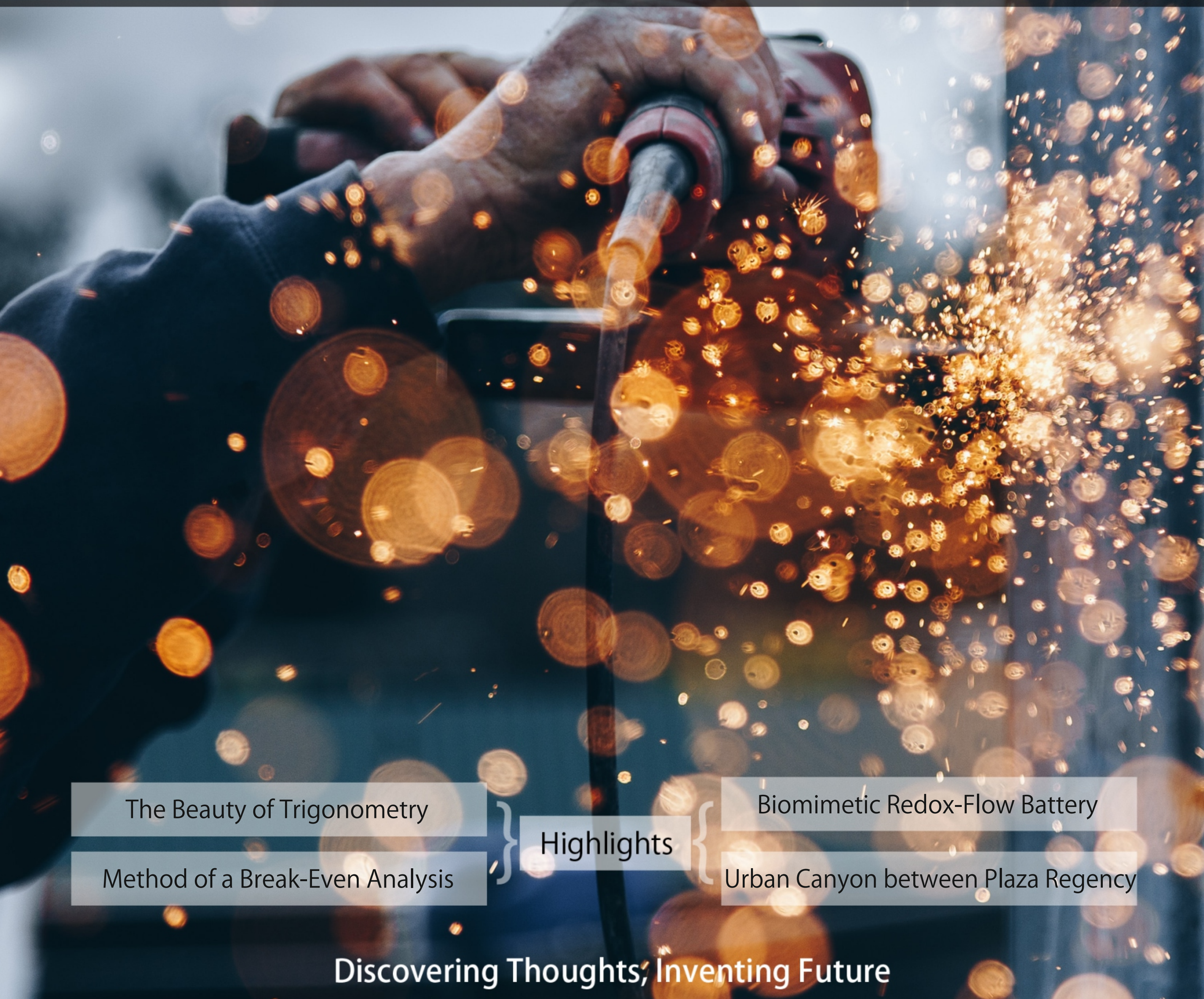

The Beauty of Trigonometry

Method of a Break-Even Analysis

Highlights

Biomimetic Redox-Flow Battery

Urban Canyon between Plaza Regency

Discovering Thoughts, Inventing Future

VOLUME 23 ISSUE 2 VERSION 1.0

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Dr. Omid Gohardani

Ph.D. Senior Aerospace/Mechanical/ Aeronautical, Engineering professional M.Sc. Mechanical Engineering, M.Sc. Aeronautical Engineering B.Sc. Vehicle Engineering Orange County, California, US

Dr. Paolo Veronesi

Ph.D., Materials Engineering, Institute of Electronics, Italy President of the master Degree in Materials Engineering Dept. of Engineering, Italy

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The Harmonic Oscillator, Complex-Dynamics Predictability, and the Beauty of Trigonometry Subharmonic Cascades towards Resonance

By Belkacem Meziane
Université d'Artois

Abstract- The forced and undamped harmonic oscillator revisits with new and fundamental aspects. The study discloses complementary and -so far overlooked- intrinsic properties. Despite its simplicity, the model is shown to be characterized by countless -theoretically unlimited- sequences of intricate solutions. Such hierarchies, including the familiar period-doubling series -or equivalently subharmonic cascades- usually typify complex nonlinear dynamical systems. The remarkable similarity between the numerically simulated and the analytically predicted solutions confers the model unquestionable credit. It takes simple trigonometry -at the reach of the willing undergraduate student- to fully grab the essence of the new outcomes.

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Strictly as per the compliance and regulations of:

The Harmonic Oscillator, Complex-Dynamics Predictability, and the Beauty of Trigonometry Subharmonic Cascades towards Resonance

Belkacem Meziane

Abstract- The forced and undamped harmonic oscillator revisits with new and fundamental aspects. The study discloses complementary and -so far overlooked- intrinsic properties. Despite its simplicity, the model is shown to be characterized by countless -theoretically unlimited- sequences of intricate solutions. Such hierarchies, including the familiar period-doubling series -or equivalently subharmonic cascades- usually typify complex nonlinear dynamical systems. The remarkable similarity between the numerically simulated and the analytically predicted solutions confers the model unquestionable credit. It takes simple trigonometry -at the reach of the willing undergraduate student- to fully grab the essence of the new outcomes.

I. Introduction

Complex dynamics usually refers to nonlinearly coupled systems. These divide into two main classes: a) the autonomous models, whose behavior depend on specific control parameters -such as the case of an unstable laser [1], and the Lorenz model of turbulence [2]- and b) the non-autonomous systems that respond nonlinearly to some harmonic excitation, externally supplied by an adequate mechanism. The dynamical properties of these systems usually rely on computer simulations. Numerous examples have been put forward to demonstrate the complex-and unpredictable- behavior of nonlinear models that are generally described in terms of coupled differential equations, which contain -at least- one nonlinear term [3-6]. However, no report has expanded the analysis of the undamped harmonic oscillator, externally driven with harmonic excitations. The usual approach to hold this simple model is limited to analytical ingredients that have become standard in introductory courses at the undergraduate level. The commonly accepted point is that sinusoidal excitations yield comparative sinusoidal responses. Our investigations reveal that such a conclusion is incomplete to explain the wealth of solutions outputting from the system.

The harmonic oscillator is -par excellence- the fundamental dynamical system, which introduces at the very first academic lectures of physics and mathematics [7-18]. The study of the autonomous scheme usually goes along with the introduction of second-order differential equations in mathematics, and the study of small-amplitude oscillations in physics, whereas the non-autonomous case is delayed until the undergraduate years, imparting in the more specific classes of mechanics and vibrations. Its properties are so largely recognized that trying to bring new elements of analysis may seem difficult, if not impossible. Yet, despite its universally acknowledged properties, we shall reveal new outcomes and features that have never been disclosed before. The new findings are based on an overlooked solution that plays an essential role in orbit modelling. Even though the new approach does not question the model's main property, i.e., its intrinsic resonant phenomenon, it unveils further complexities. The disclosures arise from extensive computer analysis. The numerical solutions are shown to follow their analytical counterparts, which are straightforwardly derived from the introduction of the overlooked solution.

The study reveals a wealth of phase-space trajectories, with sequences that stem from locking and beating mechanisms between the forcing and the resonant frequencies. These phenomena retrieve with direct numerical simulations while recovering -with staggering precision- from the new analytical ingredients.

The presentation develops according to the following hierarchy. After recalling the properties of the autonomous harmonic oscillator in Sec. II, the non-autonomous system is presented in Sec. III. Sec. IV deals with irregular signals and a periodic trajectories, while some locking phenomena and period-doubling sequences are presented in Sec. V. A few concluding remarks follow in Sec. VI, and three appendixes are integrated to give comprehensive accounts of the primary analytical aspects.

II. The Autonomous Harmonic Oscillator: The Pendulum and Mass-Spring Examples

The oscillatory movement of a simple pendulum of length l describes with the second-order differential equation.

$$\frac{d^2\theta}{dt^2} + \frac{g}{l}\sin(\theta) = 0 \quad (1a)$$

i.e.,

$$\frac{d^2\theta}{dt^2} + \omega_0^2\sin(\theta) = 0 \quad (1b)$$

Author: Université d'Artois, France. e-mail: belkacem@meziane.com

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where

$$\omega_0 = 2\pi f_0 = \sqrt{\frac{g}{l}} \quad (1c)$$

is the free-oscillator pulsation (angular frequency), and f_0 its natural frequency.

For small enough θ, i.e., $\theta \le \frac{\pi}{18}$, $\sin(\theta) \cong \theta$ (it takes a pocket calculator to check that $\sin\left(\frac{\pi}{18}\right) \cong \frac{\pi}{18}$), the equation becomes

$$\frac{d^2\theta}{dt^2} + \omega_0^2\theta = 0 \quad (2a)$$

Whose solution reads

$$\theta = \theta_0 \cos(\omega_0 t) \quad (2b)$$

The pendulum oscillates with the angular velocity

$$\frac{d\theta}{dt} = -\omega_0\ \theta_0 \sin(\omega_0 t) = \omega_0\ \theta_0 \cos\left(\omega_0 t + \frac{\pi}{2}\right) \quad (2c)$$

Showing a $\frac{\pi}{2}$ phase difference between the velocity and the displacement.

The elements of analysis apply to the case of a free mass-spring oscillator. The mass small movement $x(t)$ around the position of equilibrium satisfies

$$\frac{d^2x}{dt^2} + \omega_0^2 x = 0 \quad (3a)$$

whose solution reads,

$$x = x_0 \cos(\omega_0 t), \quad (3b)$$

for the displacement, and

$$\mathrm{v}(t) = \frac{dx}{dt} = -\omega_0\ x_0 \sin(\omega_0 t) = \mathrm{v}_0 \cos\left(\omega_0 t + \frac{\pi}{2}\right) \quad (3c)$$

for its speed.

From Eqs (3b) and (3c), we readily derive

$$\left(\frac{x}{x_0}\right)^2 + \left(\frac{\mathrm{v}}{\mathrm{v}_0}\right)^2 = 1 \quad (3d)$$

i.e., the equation of an ellipse, which represents the system's trajectory in phase space. If the maximum position and maximum speed have the same absolute values, the phase space orbit transforms into a circle. The orbit exact shape depends on the precise initial conditions, i.e., on x_0 and v_0.

Figure 1 depicts two examples corresponding to a) $x_0 = 1$, $\omega_0 = 1$, and b) $x_0 = 1$, $\omega_0 = 2$. In the figures, $y(t) = \mathrm{v}(t) = \frac{dx}{dt}$

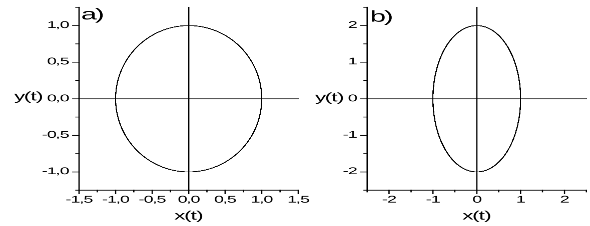

Figure 1: Phase space trajectories obtained with a) $x_0 = 1$, $\omega_0 = 1$ (circular orbit), and b) $x_0 = 1$, $\omega_0 = 2$ (elliptical trajectory).

III. The Non-Autonomous System

When some sinusoidal excitation of the form $f(t) = F\cos(\omega t)$ is supplied to the harmonic oscillator not undergoing any damping force, the mass movement describes with

$$\frac{d^2x}{dt^2} + \omega_0^2 x = F\cos(\omega t) \quad (4a)$$

As introduced in mechanics-and-vibrations lessons, the usual method of solving such an equation away from resonance, is to consider a response of the same form as the excitation, i.e.

$$x(t) = A\cos(\omega t + \varphi) \quad (4b)$$

Where amplitude A and phase φ are coefficients that must be evaluated.

Plugging Eq. (4b) into Eq. (4a), yields

$$-A\omega^2 \cos(\omega t + \varphi) + A\omega_0^2 \cos(\omega t + \varphi) = F\cos(\omega t) \quad (4c)$$

i.e.,

$$[\omega_0^2 - \omega^2]A\cos(\omega t)\cos(\varphi) - [\omega_0^2 - \omega^2]A\sin(\omega t)\sin(\varphi) = F\cos(\omega t) \quad (4d)$$

implying

$$[\omega_0^2 - \omega^2]A\sin(\varphi) = 0 \quad (4e)$$

and

$$[\omega_0^2 - \omega^2]A\cos(\omega t)\cos(\varphi) = F \quad (4f)$$

Since $\omega \neq \omega_0$, and $A \neq 0$, we are left with $\varphi = 0 \mod \pi$, and

$$A = \frac{F}{\omega_0^2 - \omega^2} \quad (4g)$$

The general solution thus reads

$$x(t) = \frac{F}{\omega_0^2 - \omega^2}\cos(\omega t) \quad (4h)$$

For the displacement, and

$$\frac{dx}{dt} = -\frac{F\omega}{\omega_0^2 - \omega^2}\sin(\omega t) \quad (4i)$$

for its speed. Note that the response is linearly correlated to the excitation, i.e.

$$x(t) = A(\omega)f(t) \quad (4j)$$

Eqs (4h) and (4i) carry the well-known phenomenon of resonance, which occurs at $\omega = \omega_0$.

The resonance curve, represented in Fig. 2, with the parameters $\omega_0 = 1$, and $F = 1$, shows the notable infinite-amplitude-catastrophe that occurs at $\omega = \omega_0$, and which was responsible for famous disasters in the past:

- On April 18, 1850, in Angers (France), a military unit crossing in cadenced steps a suspension bridge spanning the Maine river caused its destruction.
- On November 7, 1940, six months after its inauguration, the Tacoma bridge (USA) was destroyed by the effects of gusts of winds, which -without being particularly violent (60 km/h)- were regular.

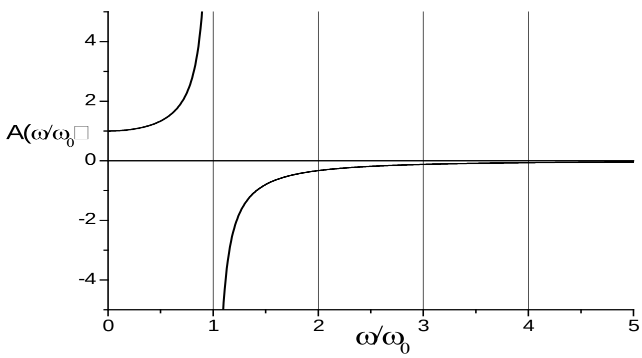

Figure 2: Resonance phenomenon which occurs when the driving frequency $f = \frac{\omega}{2\pi}$ equals the system's proper frequency $f_0 = \omega_0 /2\pi$.

To derive an expression for the growing amplitude at resonance, we must solve

$$\frac{d^2 x}{dt^2} + \omega_0^2 x = F\cos(\omega_0 t) \quad (5a)$$

With the initial conditions, $x(0) = 0$, and $dx/dt = 0$, we are left with (see appendix A for details)

$$x(t) = \frac{F}{2\omega_0} t\cos(\omega_0 t) \quad (5b)$$

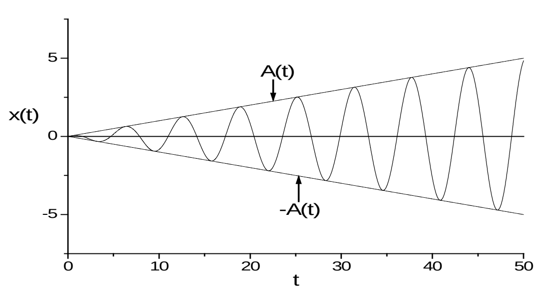

Figure 3: Displacement $x(t)$, simulated at resonance. Note the linearly growing amplitude towards infinity, following Eq. (5c).

Showing a linearly growing amplitude with respect to t, an example of which is depicted in Fig. 3.

$$A(t) = \frac{F}{2\omega_0} t \quad (5c)$$

Let us represent two typical solutions, describing with Eqs (4h) and (4i), away from resonance. Taking $F = 1$, $\omega = 0.5\omega_0$, and$\omega = 2\omega_0$, the corresponding trajectories depict with elliptical orbits, as portrayed in Fig. 4.

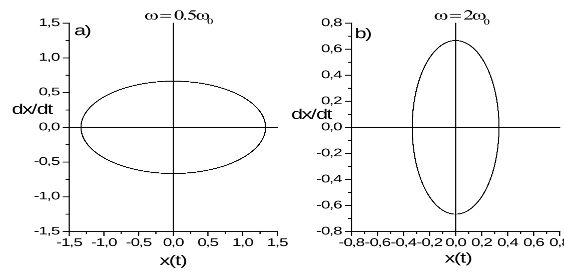

Figure 4: Elliptical orbits corresponding to Eqs (4h) and (4i), with a) $\omega = 0.5\omega_0$, and b) $\omega = 2\omega_0$.

Whatever the parameter values and initial conditions, Eqs (4h) and (4i), describe elliptical or circular orbits. That is what we teach in fundamental physics and mathematics. However, the numerical analysis of Eq. (4a) tells a different story.

To solve Eq. (4a) numerically, we introduce a y variable and obtain two coupled differential equations of the first order

$$\frac{dx}{dt} = y \quad (6a)$$

$$\frac{dy}{dt} = -\omega_0^2 x + F\cos(\omega t) \quad (6b)$$

It takes some basic numerical code, such as the second-or-fourth order Runge-Kutta algorithms, to solve Eqs (6).

The simulated solution corresponding to $F = 1$, $\omega = 0.5\omega_0$, with the initial conditions $x(0) = 0$, and $y((0) = 0$ is represented in Fig. 5. To fully sense the ingredients of the solution, we depicted the time traces, the spectrum, and the phase-space portrait. It takes this first example to grab the difference between the orbits of Fig. 4 and that of Fig. 5d. The ellipse converting into a double-loop trajectory. Such a double-loop orbit usually characterizes nonlinear systems. Since no obvious nonlinearity seems to connect x and y, in Eqs (6), one cannot but feel surprised by such an unanticipated nonlinear response: Fig. 5a clearly indicates that $x(t)$is not a pure sinusoidal function. Therefore, it is not linearly related to $f(t)$! Such a new and fundamental result is analytically derived in the following (see Eqs (8a) and (8c)).

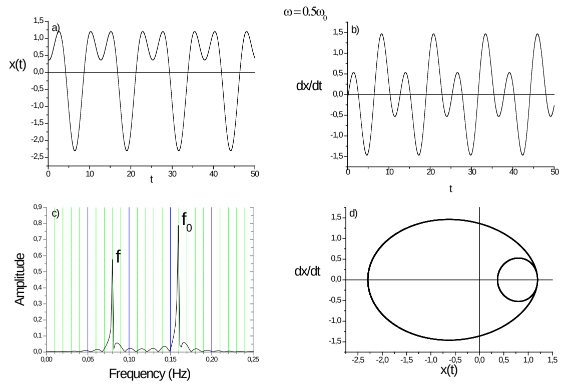

Figure 5: a) Displacement, b) speed, c) Fourier spectrum, and d) phase-space orbit, as simulated with Eqs (6), and an excitation frequency equal to half the natural one. Since we chose $\omega_0 = 1$, the fundamental frequency scales as $f_0 = \frac{1}{2\pi} \cong 0.16$.

As represented in Fig. 6, at $\omega = 2\omega_0$, we retrieve the features of Fig. 5d, which was simulated at$\omega = 0.5\omega_0$. Such a resemblance is not limited to the present example. It clarifies with the full analytical solution, as henceforth demonstrated.

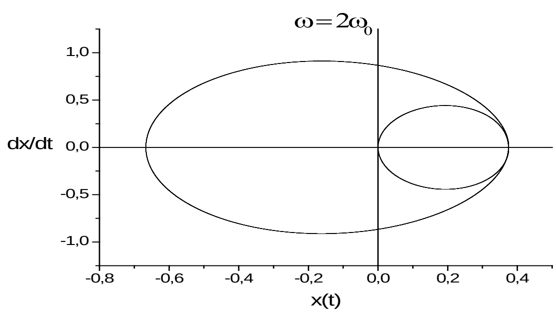

Figure 6: Phase-space orbit corresponding to $\omega = 2\omega_0$. Note the similarity with Fig. 5d.

Two other orbits, corresponding to $\omega = 0.25\omega_0$ and $\omega = 4\omega_0$ are represented in Fig. 7. Again, the two trajectories are similar.

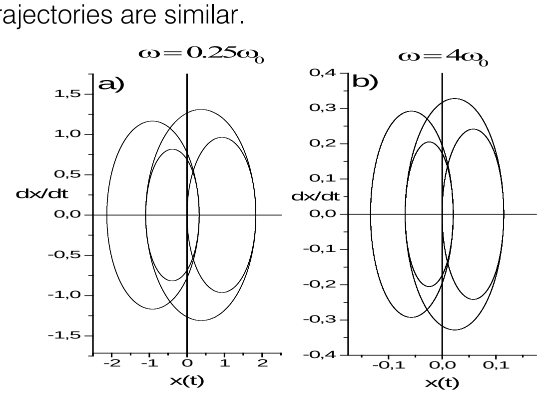

Figure 7: Simulated four-cycle orbits corresponding to a) $\omega = 0.25\omega_0$, and b)$\omega = 4\omega_0$. Note the similarity between the two trajectories. Indeed, due to their dependence on frequency, the amplitudes scale differently.

Additional trajectories, corresponding to $\omega = 5\omega_0$ and $\omega = 10\omega_0$ are represented in Figs. 8 and 9. As expected, the Fourier spectrum of Fig. 8a indicates the presence of the natural and excitation frequencies. The temporal time trace of Fig. 9a points to some well-structured modulation effect, the low frequency $f_0 - f$ modulating the high pulsation signal $f_0 + f$ (see Appendix B for detailed analytical accounts).

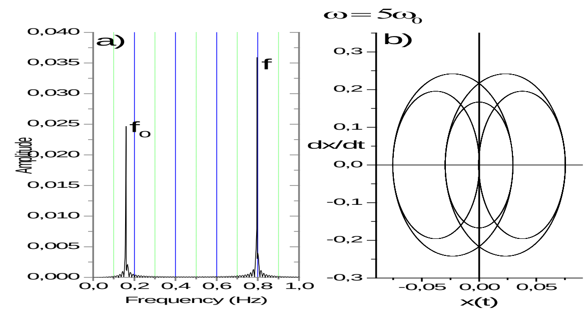

Figure 8: a) Fourier spectrum, and b) phase-space orbit, simulated with $\omega = 5\omega_0$. The trajectory is a fifth-order orbit.

In view of these unusual and unexpected results, it becomes obvious that Eq. (4h) is partial, if not unsatisfactory. As discussed above, the commonly admitted solution to Eq. (4a) is Eq. (4h). However, such a solution is incomplete because it neglects the intrinsic properties of the autonomous system

$$\frac{d^2 x}{dt^2} + \omega_0^2 x = 0 \tag{7a}$$

which must be added to Eq. (4h).

Consequently, the complete solution should read (see Appendix A for details)

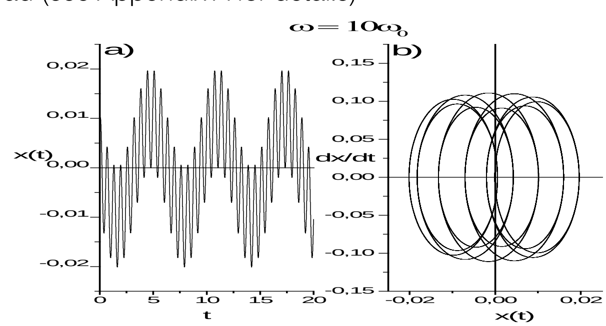

Figure 9: a) Displacement time trace in the form of modulated and modulating signals (see appendix B for details and formulations), and b) multi-loop (of the tenth order) trajectory, simulated with $\omega = 10\omega_0$.

$$x(t) = A\cos(\omega_0 t) + B\cos(\omega t) \tag{7b}$$

Which, when plugged into Eq. 4a, yields

$$-A\omega_0^2\cos(\omega_0 t) - \omega^2 B\cos(\omega t) + A\omega_0^2\cos(\omega_0 t) + B\omega_0^2\cos(\omega t) = F\cos(\omega t) \tag{7c}$$

and

$$B = \frac{F}{\omega_0^2 - \omega^2} \tag{7d}$$

$$x(t) = A\cos(\omega_0\, t) + \frac{F}{\omega_0^2 - \omega^2}\cos(\omega t) \qquad (7e)$$

Furthermore, with the initial condition $x(t) = 0$, at $t = 0$, Eq. (7e) converts into

$$x(t) = \frac{F}{\omega_0^2 - \omega^2}\left(-\cos(\omega_0\, t) + \cos(\omega t)\right) \qquad (8a)$$

While the displacement velocity expands as

$$\frac{dx}{dt} = \frac{F}{\omega_0^2 - \omega^2}\left(\omega_0\, \sin(\omega_0\, t) - \omega\sin(\omega t)\right) \qquad (8b)$$

If the initial displacement changes into $x(t) = x_0$, at $t = 0$, then $x(t)$ writes [see appendix A]

$$x(t) = \left[x_0 - \frac{F}{\omega_0^2 - \omega^2}\right]\cos(\omega_0\, t) + \frac{F}{\omega_0^2 - \omega^2}\cos(\omega t) \qquad (8c)$$

As one can see, whatever the initial conditions, the state of resonance is preserved through similar frequency dependent amplitudes.

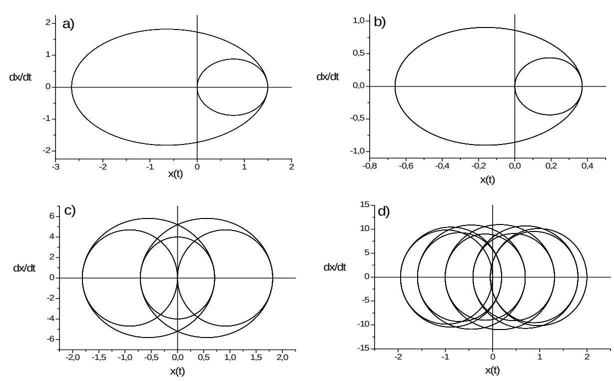

Figure 10: Phase space orbits describing with Eqs (8) and, a) $\omega = 0.5\omega_0$, b) $\omega = 2\omega_0$, c) $\omega = 5\omega_0$, and $\omega = 10\omega_0$.

Note however that -as expected from the numerical solutions- we have analytically retrieved the nonlinear nature of $x(t)$ with respect to $f(t)$, since both Eq (8a) and Eq. (8c) write as combinations of two distinct functions

$$x(t) = A(\omega)f(t) + B(\omega)g(t) \qquad (9)$$

This constitutes a major outcome of the present report. Such a fundamental result has never been highlighted in past studies. Most studies focused on the damped case, limiting the undamped one to its least ingredients. In so doing we all missed the main point about the nonlinear nature of the harmonic oscillator.

Let us use the same examples as the simulated ones and represent the solutions for $f(t) = \cos(\omega t)$, $x(0) = 0$, and respectively $\omega = 0.5\omega_0$, $\omega = 2\omega_0$, $\omega = 5\omega_0$, and $\omega = 10\omega_0$. The corresponding trajectories are depicted in Fig. 10. Indeed, if one wants to compare the associated time traces, Eq (8a) perfectly describes the features of Figs 5a, 5b and 9a, or those of any other example, provided the two involved frequencies scale commensurately to prevent irregular signals and fuzzy aperiodic trajectories.

As a last and compelling example pertaining to the validity of Eqs (8), let us solve the differential equation with $\omega = 3\omega_0$. The result is a -somewhat peculiar- three-orbit trajectory. Nonetheless, an exact replica generates with Eqs (8). It is represented in Fig. 11. Let us again note that a similar phase-space portrait obtains with $\omega = \omega_0/3$.

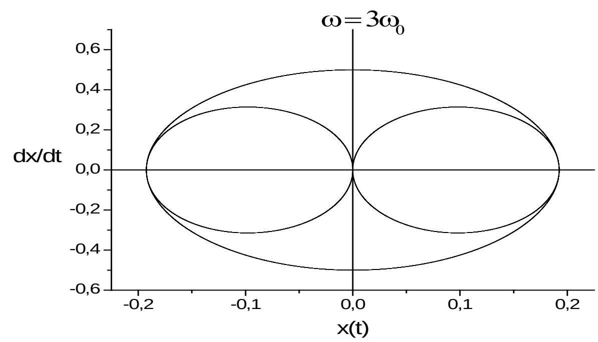

Figure 11: Analytical and numerical three-loop trajectory obtained with $\omega = 3\omega_0$, and, equivalently, with $\omega = \omega_0/3$

All these examples, and numerous others, demonstrate the validity of Eqs (8). A one-to-one comparison between the numerical and the analytical results does not call for supplementary comments, since a one-to-one correspondence obtains whatever the initial conditions or the driving frequency, as well as the forcing amplitude. F and ω may consider as the two control parameters of the system. With respect to ω, F plays a minor role.

One may therefore conclude that the general solution of the harmonic oscillator undergoing an external harmonic excitation of the form $F\cos(\omega t)$ contains both the exciting frequency f and the system's natural frequency f_0 . The above results are conclusive enough to include in future graduate and undergraduate programs that deal with oscillatory systems. The presented properties may serve as a simple introductory lesson to more complex dynamical systems.

The above examples show some worth-mentioning symmetry properties. For instance, we found the same phase portraits with $\omega = 0.5\omega_0$, and $\omega = 2\omega_0$, as well as with $\omega = 0.25\omega_0$, $\omega = 4\omega_0$; $\omega = \frac{\omega_0}{3}$, and $\omega = 3\omega_0$. i.e., whenever $\omega = n\omega_0$ or $\omega_0 = n\omega$.

In short, for any integer n such that $\omega = n\omega_0$, similar trajectories obtain with

$$x(t) = -\cos(\omega_0\, t) + \cos(n\omega_0\, t) \qquad (10a)$$

$$\frac{dx}{dt} = \omega_0 \sin(\omega_0 t) - n\,\omega_0 \sin(n\omega_0 t) \tag{10b}$$

and

$$x(t) = -\cos\left(\frac{\omega}{n} t\right) + \cos(\omega t) \tag{10c}$$

$$\frac{dx}{dt} = \frac{\omega}{n} \sin\left(\frac{\omega}{n} t\right) - \omega \sin(\omega t) \tag{10d}$$

It takes some simple graphical software to confirm these elements. Indeed, such a symmetric property is valid only for the case studied in this section, with the initial condition, $x(0) = 0$.

IV. Irregular Signals and Aperiodic Trajectories

Irregular trajectories usually characterize more complex nonlinear systems through sequences of solutions ultimately ending in chaotic signals.

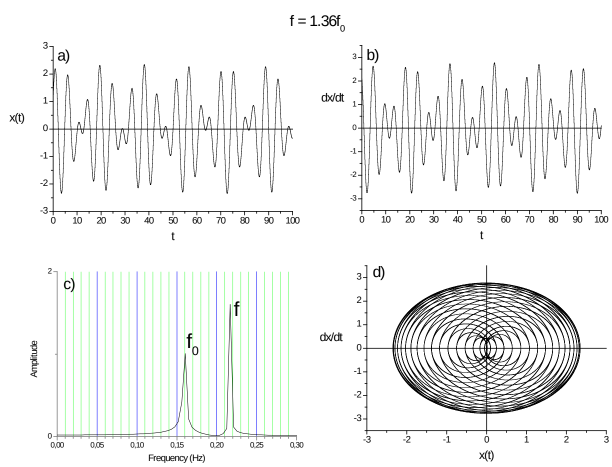

Figure 12: Analytical and numerical solution obtained with a driving frequency $f = 1.36 f_0$, a) and b) irregular time traces, c) Fourier spectrum, and d) aperiodic trajectory.

Let us represent the solution corresponding to Eq. (8c) by fixing the external frequency to incommensurately scale with the natural frequency. The example of Fig. 12 was simulated with $f = 1.36 f_0$. The displacement and velocity time traces do not show any periodicity. The phase-space trajectory is multi-loop orbit with an infinite order. The orbit was simulated limiting the time span to $t = 100$. The more we increase t, the more surface the trajectory occupies. This is an indication of aperiodicity.

The analytical descriptions of each graph in Fig. 12 obtain with the following expansions

$$x(t) = \cos(\omega_0 t) + \cos(1.36\omega_0 t) \tag{11a}$$

$$\frac{dx}{dt} = -\omega_0 \sin(\omega_0 t) - 1.36\omega_0 \sin(1.36\omega_0 t) \tag{11b}$$

Again, outstanding similarities appear between the numerically simulated graphs of Fig. 12 and the analytical counterparts depicted in Fig. 13.

Two frequency chaos has long been reported in complex systems [14]. However, to the best of our knowledge, it demonstrates here analytically for the first time, in the case of a harmonic oscillator. It takes Eqs (11), or any other expansions, with two incommensurate frequencies, to obtain irregular trajectories. As time flows, the orbits fill the entire plane, an indication of the aperiodic nature of the solution.

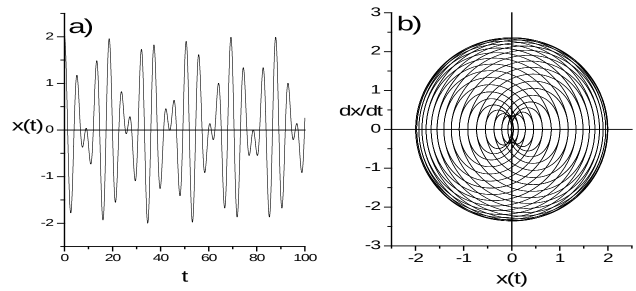

Figure 13: a) Irregular time trace, and b) aperiodic trajectory, obtained with Eqs (11).

Noteworthy is the fact that slight changes in driving frequencies transform well-structured signals and orbits into aperiodic time traces and trajectories. These may consider as further examples of the famous butterfly effect, which demonstrates in other nonlinear systems, such as the Lorenz attractor [2, 15].

V. Locking Phenomena and Generation of Sub-Harmonic Sequences

The sequence of period-doubling-or, equivalently, subharmonic cascading- is known in nonlinear dynamics as a route towards deterministic chaos [15]. Phase space trajectories with period doubling sequences also characterize the forced harmonic oscillator, as hereafter demonstrated in several cases with distinct control parameters and initial conditions.

a) *Period doubling sequence generated with* $f(t) = 0.1\sin(\omega t)$, $\omega_0 = 1$, *and* $x_0 = 0$.

In this case, the solution expands into (see Appendix A)

$$x(t) = \frac{F}{\omega_0^2 - \omega^2}\left(-\frac{\omega}{\omega_0} \sin(\omega_0 t) + \sin(\omega t)\right) \tag{12a}$$

and

$$y(t) = \frac{dx}{dt} = \frac{F\omega}{\omega_0^2 - \omega^2}\left(-\cos(\omega_0 t) + \cos(\omega t)\right) \tag{12b}$$

The trajectories obtained both numerically and analytically, successively with $\omega = 2\omega_0$ (period one), $\omega = 1.5\omega_0$ (period two), $\omega = 1.25\omega_0$ (period four), and $\omega = 1.21\omega_0$ (aperiodic, the driving and natural

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frequencies scale incommensurately), are represented in Fig. 14.

The full sequence of period doubling towards resonance generates with

$\omega_1 = 2\omega_0$,

$\omega_2 = 2\omega_0 - \frac{1}{2}\omega_0$,

$\omega_4 = \omega_{2^2} = 2\omega_0 - \left(\frac{1}{2} + \left(\frac{1}{2}\right)^2\right)\omega_0$,

$\omega_8 = \omega_{2^3} = 2\omega_0 - \left(\frac{1}{2} + \left(\frac{1}{2}\right)^2 + \left(\frac{1}{2}\right)^3\right)\omega_0$,

…

$\omega_{2^n} = 2\omega_0 - \left(\frac{1}{2} + \left(\frac{1}{2}\right)^2 + \left(\frac{1}{2}\right)^3 + \cdots \left(\frac{1}{2}\right)^n\right)\omega_0$,$\omega_{2^\infty} = \omega_0$ (resonance (aperiodic)).

Each cycle of the sequence generates with Eqs (12).

Note that

$\sum_{n=1}^{n} \frac{1}{2^n} = \frac{1-\left(\frac{1}{2}\right)^{n+1}}{1-\frac{1}{2}} - 1 = 1 - \left(\frac{1}{2}\right)^n$,

$\omega_{2^n} = 2\omega_0 - \left(1 - \left(\frac{1}{2}\right)^n\right)\omega_0 = \left(1 + \left(\frac{1}{2}\right)^n\right)\omega_0$,

and

$\omega_0^2 - \omega_{2^n}^2 = \omega_0^2 - \left(1 + \left(\frac{1}{2}\right)^n\right)^2 \omega_0^2 = -\left(2\left(\frac{1}{2}\right)^n + \left(\frac{1}{2}\right)^{2n}\right)\omega_0^2 = -\left(\frac{1}{2}\right)^{n-1}\left(1 + \left(\frac{1}{2}\right)^{n+1}\right)\omega_0^2$.

Also note that the state of resonance is reached at $\omega_{2^\infty} = \left(1 + \left(\frac{1}{2}\right)^\infty\right)\omega_0 = \omega_0$.

The complete sub-harmonic cascade depicts -and predicts- analytically with the following formulas

$$x_{2^n}(t) = \frac{F}{\omega_0^2 - \omega_{2^n}^2}\left(-\frac{\omega_{2^n}}{\omega_0}\sin(\omega_0 t) + \sin(\omega_{2^n} t)\right) \quad (13a)$$

$$y_{2^n}(t) = \frac{F\omega_{2^n}}{\omega_0^2 - \omega_{2^n}^2}\left(-\cos(\omega_0 t) + \cos(\omega_{2^n} t)\right) \quad (13b)$$

With $\omega_{2^n} = \left(1 + \left(\frac{1}{2}\right)^n\right)\omega_0$, $n = 0, 1, 2, 3\ldots$

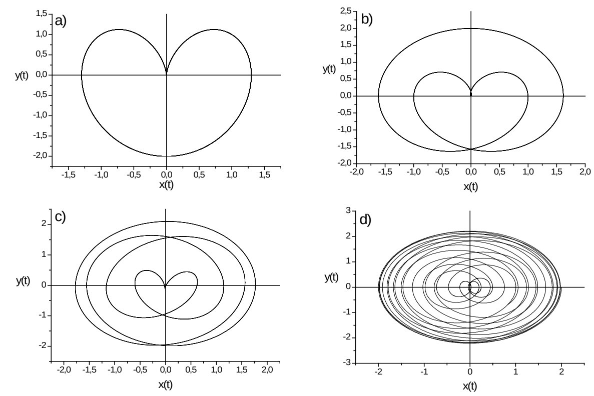

Figure 14: Period doubling sequence, analytically replicated with a) $\omega = 2\omega_0$ (period one), b) $\omega = 1.5\omega_0$ (period two), c) $\omega = 1.25\omega_0$ (period four), and d) $\omega = 1.21\omega_0$ (aperiodic orbit).

The order of the trajectory corresponds to the value of 2^n. For example, $2^0 = 1$ (period one), $2^2 = 4$ (period four), $2^3 = 8$ (period eight), $2^4 = 16$ (period sixteen), etc.

According to Eqs (13), the period-8 trajectory follows

$$x_8(t) = -\frac{6.4}{17}(-1.125\sin(t) + \sin(1.125t)) \quad (14a)$$

$$y_8(t) = -\frac{7.2}{17}(-\cos(t) + \cos(1.125t)) \quad (14b)$$

where $\omega_8 = \left(1 + \left(\frac{1}{2}\right)^3\right)\omega_0 = \frac{9}{8}\omega_0$.

We leave the reader with the simple task to replicate the corresponding orbit with any graphical software to confirm the associated periodicity. Indeed, one may -for the purpose of corroboration- confirm that exact replicas of the trajectories generate, as well, with numerical simulations of Eqs. (6).

b) *Period doubling sequence generated with* $f(t) = 0.1\,sin\,(\omega t)$, $\omega_0 = 1$, *and* $x_0 = 1$.

In this case, the solution expands into (see Appendix A)

$$x(t) = \frac{F}{\omega_0^2 - \omega^2}\left(-\frac{\omega}{\omega_0}\sin(\omega_0 t) + \sin(\omega t)\right) + x_0\,cos(\omega_0 t) \quad (15a)$$

$$y(t) = \frac{dx}{dt} = \frac{F\omega}{\omega_0^2 - \omega^2}\left(-\cos(\omega_0 t) + \cos(\omega t)\right) - x_0\,sin(\omega_0 t) \quad (15b)$$

The trajectories generated both numerically and analytically, successively with $\omega = 2\omega_0$ (period one), $\omega = 0.5\omega_0$ (period two), $\omega = 0.75\omega_0$ (period four) and $\omega = 0.875\omega_0$ (period eight) are represented in Fig. 15.

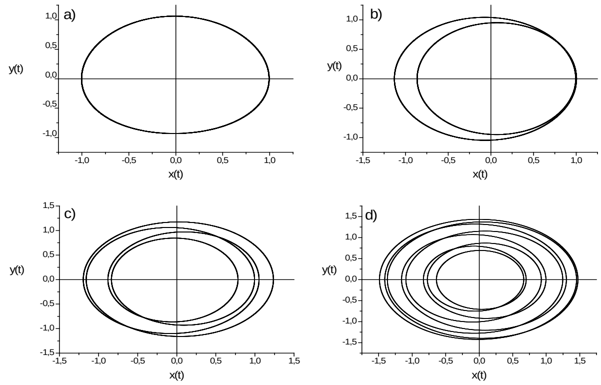

Figure 15: Period doubling sequence analytically replicated with a) $\omega = 2\,\omega_0$ (period one), b) $\omega = 0.5\,\omega_0$ (period two), c) $\omega = 0.75\,\omega_0$ (period four), and d) $\omega = 0.875\,\omega_0$ (period eight).

c) Period doubling sequence generated with $f(t) = 0.1 cos\,(\omega t)$, $\omega_0 = 1$, and $x_0 = 0$.

The solution describes with

$$x(t) = \frac{0.1}{1-\omega^2}(-\cos(t) + \cos(\omega t)) \qquad (16a)$$

$$y(t) = \frac{dx}{dt} = \frac{0.1}{1-\omega^2}(\sin(t) - \omega\sin(\omega t)) \qquad (16b)$$

The trajectories obtained both numerically and analytically successively with $\omega = 0.5\omega_0$ (period two), $\omega = 0.75\omega_0$ (period four), $\omega = 0.875\omega_0$ (period eight) and $\omega = \omega_0$ (resonance (aperiodic signal)) are represented in Fig. 16.

As in subsection a), the full sequence of period doubling towards resonance follows

$\omega_2 = \frac{\omega_0}{2}$,

$\omega_4 = \left(\frac{1}{2} + \frac{1}{4}\right)\omega_0$,

$\omega_8 = \left(\frac{1}{2} + \frac{1}{4} + \frac{1}{8}\right)\omega_0$,

$\omega_{16} = \left(\frac{1}{2} + \frac{1}{4} + \frac{1}{8} + \frac{1}{16}\right)\omega_0$,....

$\omega_{2^n} = \left(\frac{1}{2} + \frac{1}{4} + \frac{1}{8} + \cdots \frac{1}{2^n}\right)\omega_0$,

....

$\omega_{2^\infty} = \omega_0$ (resonance (unbounded aperiodic signal)). Each cycle of the sequence describes analytically with Eqs (16).

Undoubtedly, this is the first report on nonlinear dynamics in which subharmonic cascades generate analytically. The main physical mechanism behind such cascades is a locking phenomenon that takes place between the driving and the natural frequencies. Such looking mechanism occurs whenever the ratio between these two frequencies is a rational number.

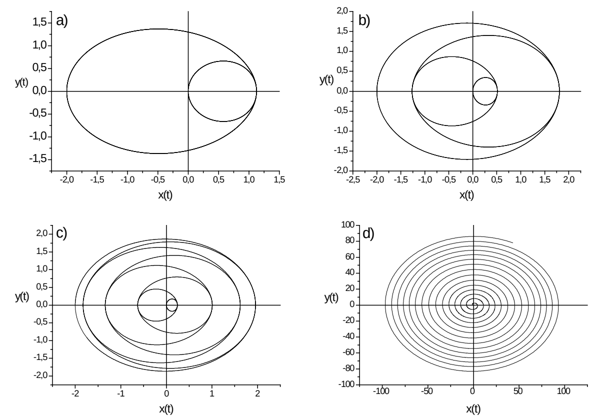

Figure 16: Trajectories obtained both numerically and analytically, a) with $\omega = 0.5\omega_0$ (period two), b) $\omega = 0.75\omega_0$ (period four), c) $\omega = 0.875\omega_0$ (period eight), and d) $\omega = \omega_0$ (resonance, with an aperiodic structure).

Let us note that the period doubling sequence generated with the conditions $x_0 = 1$, $f(t) = 0.1\cos(\omega t)$, and $\omega_0 = 1$ is identical to that found in subsection b), with $x_0 = 1$, and $f(t) = 0.1\sin(\omega t)$. We leave the generation of this supplementary cascade as an exercise to the reader. To enable such a simple task, the associated formulas are comprehensively derived and summarized in appendix A.

In view of the results of Subsect. a)-c), one may so conclude that period-doubling towards resonance is an intrinsic property of the externally driven harmonic oscillator. Other complex structures obtain by varying the main control parameter ω while fixing *F* to any arbitrary value.

d) Additional trajectories generated with $f(t) = 0.1\,sin\,(\omega t)$, $\omega_0 = 1$, and $x_0 = 0$.

The corresponding analytical expansions read

$$x(t) = \frac{0.1}{1-\omega^2}(-\,\omega\sin(t) + \sin(\omega t)) \qquad (17a)$$

$$y(t) = \frac{dx}{dt} = \frac{0.1\omega}{1-\omega^2}(-\cos(t) + \cos(\omega t)) \qquad (17b)$$

The trajectories simulated both numerically and analytically, successively with $\omega = 3\,\omega_0$ (double loop structure), $\omega = 5\,\omega_0$ (four loop trajectory), $\omega = 4\,\omega_0$ (symmetric orbit) and $\omega = 2.5\,\omega_0$ (asymmetric trajectory) are depicted in Fig. 17.

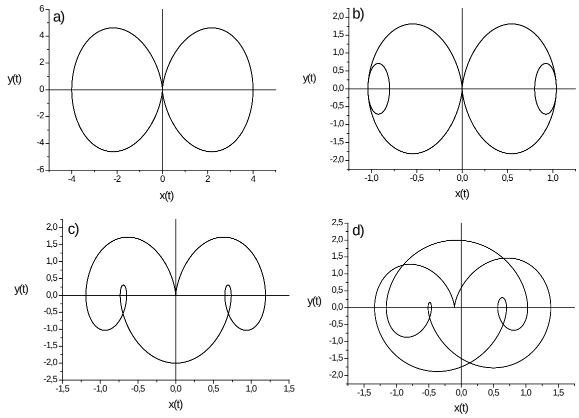

Figure 17: Trajectories obtained both numerically and analytically, successively with a) $\omega = 3\omega_0$, b) $\omega = 5\omega_0$, c) $\omega = 4\omega_0$, and d) $\omega = 2.5\omega_0$. Again, note the commensurate scaling between the driving and the natural frequencies.

These examples were arbitrarily chosen amongst countless others. Almost any orbit -with simple or complex structure- may be generated by randomly fixing the system's control parameters and initial conditions. To avoid fuzzy aperiodic trajectories -as that of Fig. 14d- the driving and natural frequencies must scale commensurately.

Let us recall that two quantities are commensurable if their ratio is a rational number. If not, these are incommensurable.

As a final statement added in proof, let us bring the attention to the fact that an intrinsic nonlinearity carries through the sine or cosine of the external excitation. Consequently, despite its apparent simplicity, the forced harmonic oscillator is a nonlinear system. As such, its behavior has much to share with other nonlinear structures. The originality here is the fact that given the set of initial conditions and the values of the two control parameters, the system's dynamics is fully *predictabl*e, through analytical developments of the solutions with a simple relationship, which relates the oscillator movement to the excitation $f(t)$ and to the natural solution $g(t)$, i.e., $x(t) = A(\omega)f(t) + B(\omega)g(t)$.

Appendix A summarizes the complete series of solution structures, which connect to the precise initial conditions. These condensate into four formulas that give comprehensive accounts of the predictable dynamics.

Let us finally add that if we introduce a third variable, $z = \omega t$, the model transforms into three nonlinearly coupled differential equations of the form

$$\frac{dx}{dt} = y \qquad (18a)$$

$$\frac{dy}{dt} = -\omega_0^2 x + F\cos(z) \qquad (18b)$$

$$\frac{dz}{dt} = \omega \qquad (18c)$$

Therefore, it should not be surprising that the model's dynamics carries the same complexities as those of any other nonlinear structure with three degrees of freedom. One non-linear term, i.e., $\cos(z)$, is all it takes to generate a wealth of periodic and aperiodic solutions, with the external frequency as the primary control parameter. The main difference with other nonlinear systems is the depiction of any phase-space trajectory without calling for computer routines, except for the purpose of corroboration and consistency with the analytical formulations.

VI. Conclusion

We have revisited the forced-and-undamped harmonic oscillator and disclosed so far overlooked solutions that carry intrinsic nonlinearities. Extensive numerical and analytical examinations give full credit to the outcomes. Despite the complex dynamics these hold, our findings are simple enough to promote their introduction into academic courses in mechanics and vibrations, as well as in mathematics classes that deal with second-order differential equations. The model may serve as a basic example to introduce more complex dynamical systems [12, 15] and familiarize the student with the simple construction of phase space orbits and sequences such as period doubling that were shown to stem from a simple locking phenomenon between the driving frequency and the system's natural frequency. Let us point out the fact that it takes a simple graphical calculator to depict any analytical signal or trajectory. Since the system depends on two control parameters - the amplitude and frequency of the external excitation- that may arbitrarily be selected, the number of solutions, and phase-space trajectories, is theoretically unlimited.

Worth insisting on is the construction- unquestionably for the first time in a research and pedagogical paper dedicated to the study of nonlinear dynamical systems- of a series of analytical subharmonic cascades towards resonance. With this respect, our analysis makes clear the fact that period doubling is an intrinsic characteristic that structures systematically and predictably in the case of the forced harmonic oscillator, when the driving and natural frequencies scale commensurately. In addition, next to the unbounded state of resonance, aperiodicity -with bounded trajectories- is the rule whenever the two frequencies scale incommensurately, i.e., when their ratio is a not a rational number.

Appendix A

Comprehensive review of the non-autonomous system

Let us write the second order differential equation that describes the forced harmonic oscillator when it is driven with an external excitation of the form

$$f(t) = F\sin(\omega t)$$

$$\frac{d^2x}{dt^2} + \omega_0^2 x = F\sin(\omega t) \qquad \text{(A1a)}$$

Considering the free oscillator properties, the general solution reads

$$x(t) = Asin(\omega_0 t) + Bcos(\omega_0 t) + Csin(\omega t) + Dcos(\omega t) \qquad \text{(A1b)}$$

implying

$$\frac{d^2x}{dt^2} = -A\omega_0^2\sin(\omega_0 t) - B\omega_0^2\cos(\omega t) - C\omega^2\sin(\omega t) - D\omega^2\cos(\omega t) \qquad \text{(A1c)}$$

So that

$$(\omega_0^2 - \omega^2)Csin(\omega t) + (\omega_0^2 - \omega^2)Dcos(\omega t) = F\sin(\omega t) \qquad \text{(A1d)}$$

With the solutions

$$D = 0 \qquad \text{(A1e)}$$

and

$$C = \frac{F}{\omega_0^2 - \omega^2} \qquad \text{(A1f)}$$

The solution writes

$$x(t) = Asin(\omega_0 t) + Bcos(\omega_0 t) + \frac{F}{\omega_0^2 - \omega^2}\sin(\omega t) \qquad \text{(A2a)}$$

A and *B* obtain with precise initial conditions.

In the case where $\frac{dx}{dt} = 0$, at $t = 0$, we obtain

$$A\omega_0 + \frac{F}{\omega_0^2 - \omega^2}\omega = 0 \qquad \text{(A2b)}$$

i.e.,

$$A = -\frac{F}{\omega_0^2 - \omega^2}\frac{\omega}{\omega_0} \qquad \text{(A2c)}$$

If at $t = 0$, $x(0) = 0$, then $B = 0$, and the solution writes

$$x(t) = \frac{F}{\omega_0^2 - \omega^2}\left(-\frac{\omega}{\omega_0}\sin(\omega_0 t) + \sin(\omega t)\right) \qquad \text{(A2d)}$$

If at $t = 0$, $x = x_0$, then $B = x_0$, and

$$x(t) = \frac{F}{\omega_0^2 - \omega^2}\left(-\frac{\omega}{\omega_0}\sin(\omega_0 t) + \sin(\omega t)\right) + x_0\cos(\omega_0 t) \qquad \text{(A3)}$$

If the system is driven with $f(t) = F\cos(\omega t)$, the equation writes

$$\frac{d^2x}{dt^2} + \omega_0^2 x = F\cos(\omega t) \qquad \text{(A4a)}$$

The solution is not quite the same as Eqs (A2d) and (A3). It expands into

$$x(t) = Acos(\omega_0 t) + Bsin(\omega_0 t) + Ccos(\omega t) + Dsin(\omega t) \qquad \text{(A4b)}$$

Which, when plugged into Eq. A(4a) yields

$$(\omega_0^2 - \omega^2)Ccos(\omega t) + (\omega_0^2 - \omega^2)Dsin(\omega t) = F\cos(\omega t) \qquad \text{(A4c)}$$

i.e.

$$D = 0 \tag{A4d}$$

and

$$C = \frac{F}{\omega_0^2-\omega^2} \tag{A4e}$$

The solution writes

$$x(t) = A\cos(\omega_0\, t) + B\sin(\omega_0\, t) + \frac{F}{\omega_0^2-\omega^2}\cos(\omega t) \tag{A5a}$$

If, at $t = 0$, $x = x_0$, then

$$A = x_0 - \frac{F}{\omega_0^2-\omega^2} \tag{A5b}$$

We determine B with $dx/dt = 0$, at $t = 0$

$$\frac{dx}{dt} = -A\omega_0 \sin(\omega_0\, t) + B\omega_0 \cos(\omega_0\, t) - C\omega \sin(\omega\, t) + D\omega \cos(\omega_0\, t) = 0 \tag{A5c}$$

From which we extract, $B = D = 0$, and

$$x(t) = \left(x_0 - \frac{F}{\omega_0^2-\omega^2}\right)\cos(\omega_0\, t) + \frac{F}{\omega_0^2-\omega^2}\cos(\omega t) \tag{A5d}$$

i.e.

$$x(t) = \frac{F}{\omega_0^2-\omega^2}\left(-\cos(\omega_0\, t) + \cos(\omega t)\right) + x_0 \cos(\omega_0\, t) \tag{A5e}$$

The case corresponding to $x(0) = 0$ is considered in the text. See Eq. (8a) or Eq. (A7c).

Solution at resonance

For $\omega = \omega_o$, Eq. (A4a) writes

$$\frac{d^2x}{dt^2} + \omega_0^2 x = F\cos(\omega_0\, t) \tag{A6a}$$

Since we know that at resonance the amplitude grows indefinitely, we try the following solution

$$x(t) = At\sin(\omega_0\, t) + Bt\cos(\omega_0\, t) \tag{A6b}$$

Transforming Eq. (A6a) into

$$2\omega_0 A\cos(\omega_0\, t) - 2\omega_0 B\sin(\omega_0\, t) = F\cos(\omega_0\, t) \tag{A6c}$$

i.e.

$$B = 0 \tag{A6d}$$

and

$$A = \frac{F}{2\omega_0} \tag{A6e}$$

The general solution expands into

$$x(t) = c_1 \sin(\omega_0\, t) + c_2 \cos(\omega_0\, t) + \frac{F}{2\omega_0} t\cos(\omega_0\, t) \tag{A6f}$$

With the initial conditions $x(0) = 0$ and $dx/dt = 0$, we are left with

$$x(t) = -\frac{F}{2\omega_0^2}\sin(\omega_0\, t) + \frac{F}{2\omega_0} t\cos(\omega_0\, t) \tag{A6g}$$

For large $t's$, the first term becomes negligible, and

$$x(t) = \frac{F}{2\omega_0} t\cos(\omega_0\, t) \tag{A6h}$$

Indicative of linearly growing amplitudes, conforming to the graph of Fig. 3.

Summary of the solutions

For straightforward comparisons between the formulas -and forthright signal and orbit depictions- let us summarize the solutions.

a) $f(t) = F\sin(\omega t),\ x(0) = 0$

$$x(t) = \frac{F}{\omega_0^2-\omega^2}\left(-\frac{\omega}{\omega_0}\sin(\omega_0\, t) + \sin(\omega t)\right) \quad \text{(A7a)}$$

b) $f(t) = F\sin(\omega t),\ x(0) = x_0$

$$x(t) = \frac{F}{\omega_0^2-\omega^2}\left(-\frac{\omega}{\omega_0}\sin(\omega_0\, t) + \sin(\omega t)\right) + x_0\ \cos(\omega_0\, t) \quad \text{(A7b)}$$

c) $f(t) = F\cos(\omega t),\ x(0) = 0$

$$x(t) = \frac{F}{\omega_0^2-\omega^2}(-\cos(\omega_0\, t) + \cos(\omega t)) \quad \text{(A7c)}$$

d) $f(t) = F\cos(\omega t),\ x(0) = x_0$

$$x(t) = \frac{F}{\omega_0^2-\omega^2}(-\cos(\omega_0\, t) + \cos(\omega t)) + x_0\ \cos(\omega_0\, t) \quad \text{(A7d)}$$

As fully demonstrated in the text, through the subharmonic sequences, even though only slight differences appear between the four expressions, each formula carries distinctive dynamics.

Again, let us insist on the fact that, whatever the initials conditions, all four formulas bear the form $x(t) = A(\omega)f(t) + B(\omega)g(t)$. An indication of the nonlinear dependence of the oscillator displacement with respect to the external excitation.

Indeed, if we represent $x(t)$ vs $f(t)$, we recover a linear segment in the case of a linear response (Fig.A1-a) and a nonlinear curve in the case of nonlinear response (Fig.A1-b). Both curves correspond to $F = 1$, $\omega_0 = 1$, and $\omega = 2\omega_0$.

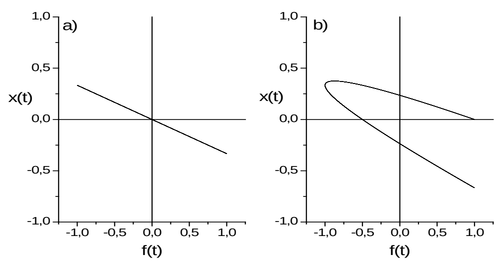

Figure A1: Response $x(t)$ vs excitation $f(t)$, in the case of a) a linear solution, and b) a nonlinear solution.

Appendix B

Useful trigonometry

To understand the modulation effect that occurs in the presence of the driving and the natural frequencies, it is useful to establish the following relationship

$$\cos(\omega_0\, t) - \cos(\omega t) = 2\sin\left(\frac{\omega+\omega_0}{2}t\right)\sin\left(\frac{\omega-\omega_0}{2}t\right) \quad \text{(B1a)}$$

Let us start with

$$\cos(\omega t) = \cos\left(\frac{\omega+\omega_0}{2}t + \frac{\omega-\omega_0}{2}t\right) \quad \text{(B1b)}$$

which transforms into

$$\cos(\omega t) = \cos\left(\frac{\omega+\omega_0}{2}t\right)\cos\left(\frac{\omega-\omega_0}{2}t\right) - \sin\left(\frac{\omega+\omega_0}{2}t\right)\sin\left(\frac{\omega-\omega_0}{2}t\right) \quad \text{(B1c)}$$

Furthermore

$$\cos(\omega_0\, t) = \cos\left(\frac{\omega+\omega_0}{2}t - \frac{\omega-\omega_0}{2}t\right) \quad \text{(B1d)}$$

converts into

$$\cos(\omega_0\, t) = \cos\left(\frac{\omega+\omega_0}{2}t\right)\cos\left(\frac{\omega-\omega_0}{2}t\right) + \sin\left(\frac{\omega+\omega_0}{2}t\right)\sin\left(\frac{\omega-\omega_0}{2}t\right) \quad \text{(B1e)}$$

So that

$$-\cos(\omega_0\, t) + \cos(\omega t) = -2\sin\left(\frac{\omega+\omega_0}{2}t\right)\sin\left(\frac{\omega-\omega_0}{2}t\right) \quad \text{(B1f)}$$

and

$$x(t) = \frac{F}{\omega_0^2 - \omega^2}\left(-\cos(\omega_0\, t) + \cos(\omega t)\right) = -\frac{2F}{\omega_0^2 - \omega^2}\sin\left(\frac{\omega+\omega_0}{2}t\right)\sin\left(\frac{\omega-\omega_0}{2}t\right) \quad \text{(B1g)}$$

This last relation indicates that in the presence of the driving and natural solutions, the signal outputs in the form of a high frequency component $f + f_0$ modulated by a lower frequency at $f - f_0$, an example of which is represented in Fig. 9a of the text.

Also note that the amplitude of the displacement is twice that obtained when the natural solution is neglected (compare Eq. (B1g) and Eq. (4h) of the text). This means that the resonant phenomenon becomes more important when the free oscillator frequency is included. Consequently, added to the butterfly effect, which transforms regular signals into turbulent ones whenever the driving and natural frequencies scale incommensurately, catastrophes -as those described in the text- are (were) more likely to occur!

APPENDIX C

Note added in proof

Let us rewrite Eqs (6)

$$\frac{dx}{dt} = y \quad \text{(C1a)}$$

$$\frac{dy}{dt} = -\omega_0^2 x + F\cos(\omega t) \quad \text{(C1b)}$$

And define a new variable

$$z = \omega t \quad \text{(C2a)}$$

So that

$$\frac{dz}{dt} = \omega \quad \text{(C2b)}$$

Eqs (C1) rewrite in the form

$$\frac{dx}{dt} = y \quad \text{(C3a)}$$

$$\frac{dy}{dt} = -\omega_0^2 x + F\cos(z) \quad \text{(C3b)}$$

$$\frac{dz}{dt} = \omega \quad \text{(C3c)}$$

We are in the presence of a three-dimensional system nonlinearly coupled through the term $\cos(z)$.

Therefore, it should be of no surprise to retrieve typical properties of other nonlinearly coupled differential equations as fully described in the text [12].

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By N.M. Kocherginsky

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BIOMIMETICREDOXFLOWBATTERYWITHOUTTRADITIONALELECTRODES

Strictly as per the compliance and regulations of:

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N.M. Kocherginsky

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I. Introduction

In 1780 Italian biologist and physicist Luigi Galvani and his wife, Lucia, discovered that the muscles of dead frogs' legs twitched when struck by an electrical spark [1]. Now regulation of a cell, tissue, and organ-level behavior as the result of electrically mediated signaling is called bioelectricity. It is based on ion fluxes through biological membranes, and in equilibrium transmembrane electric potential difference ΔE for an ideally ion-selective membrane is described by Nernst equation

$$\Delta E = -\frac{2.3RT}{zF}\log\frac{c_2}{c_1} \quad (1)$$

Here c_1 and c_2 are concentrations of the permeable ion in two separated by the membrane solutions. The coefficient $2.3RT/zF$ for monocharged cations (z=+1) at room temperature is near 60 mV, and transmembrane voltage through biological membranes for 100-fold ratio c_1/c_2 is near 120 mV. Nevertheless, the stack of many membranes in an electric organ of South American electric eels may generate remarkably high voltage. For example, the recently discovered strongest bioelectricity generator *Electrophorus voltaic* (named after Volta!) generates up to 860V, but the duration of the discharge is only 1.7 ms [2].

Alessandro Volta realized that the frog's leg served both as a conductor and as a detector of electricity. He also understood that the frog's legs twitching may be caused by the two different metals connected one with another and with a frog leg. When he replaced the frog's leg with a brine-soaked paper or cardboard, he detected the flow of electricity. Later, as a result of a professional disagreement over advocated by Galvani mechanism, in 1800 Volta invented the first electric battery, now known as a voltaic pile. Its original may be found in the Volta temple in Como, near Milan. Volta also demonstrated that an effective and easily available pair of dissimilar metals to produce electricity was zinc and copper [3].

In physical terms, we say that two dissimilar metals have different Fermi levels of their electrons. In electrochemistry we use the misleading term Galvani potential to describe the electric potential difference between two points in the bulk of two metals. This difference leads to redox half-reactions on the metal surfaces in contact with brine. Zinc, as a more active metal, becomes partially dissolved in the acidic electrolyte solution as an oxidized form Zn^{2+}. If both metals are separated in space but connected outside the electrochemical system via wires, the released electrons are transferred to a less active metal, such as Cu. Cu^{2+} in a solution serves as an oxidant, converting into metal and taking electrons. Separated in space metals in this case are called electrodes. Zn electrode is called an anode, and Cu^{2+}electrode is a cathode. Formation of cations near the anode and disappearance near the cathode leads to the redistribution of ions in the brine, i.e., to the ionic current in the aqueous electrolyte.

In a homogeneous solution electron-transfer reactions between mixed redox components do not lead to an electric current. Volta's genius was that he separated the half-reactions in space, but they are still connected via ion transport in the electrolyte and electron transport outside the electrochemical cell. Since Volta's pile, all electrochemical batteries have a series of electrochemical cells. Two electrodes in each cell are separated by ionic electrolyte, but they are also connected to electrodes in the neighboring cells. Each of them serves as a source of energy, providing an elementary voltage in the battery. Later it was suggested to use ion-exchange membranes as separators inside the electrochemical cell, so that electrolyte solutions in contact with the anode and cathode may have different compositions, including pH optimized for each of the half redox reactions.

In the open circuit, initial transfer of electrons leads to charge separation. The difference of chemical properties (more accurately, the difference of redox potentials) of electrodes leads to voltage generation between two electrodes. After that new electron cannot

Author: *Next-ChemX, UIUC. e-mail: nm_koch@yahoo.com*

be transferred against electric potential difference, but if the whole cycle is not broken anywhere (closed circuit), also the continuous electric current, carried by electrons outside the electrochemical cells and by ions inside the cells, is observed.

Voltage generation using electrode-based systems has a serious advantage in comparison to the situation with biological membranes because it is based on redox reactions of different species. The Nernst equation now includes the difference of standard redox potentials ΔE_0 between an oxidant and reducing agent. The standard redox potentials in aqueous solutions are for semireactions $Zn^{2+} + 2e^- = Zn(s),\ E_0 = -0.76V$ and $Cu^{2+} + 2e^- = Cu(s),\ E_0 = +0.337V$, so that $\Delta E_0 = 1.1V$. The Nernst equation now becomes

$$\Delta E = \Delta E_0 - \frac{2.3RT}{zF} \log \frac{c_{o1} c_{r2}}{c_{r1} c_{o2}} \qquad (2)$$

Biological membrane-based "electrochemical cells" give much lower voltage, but they do not have metal-based electrodes. Their advantages are smaller size, smaller weight, possibility to work at neutral pH, etc. It seems attractive to develop not an ion-selective, but an electron-selective membrane. Well-known bilayer lipid membranes, used as a model of biological membranes, are not good for this purpose at least because they have very high specific electric resistance ($\sim M\Omega \times cm$) [4]. Previously developed by us biomimetic membrane, which is a simple nitrocellulose filter impregnated by long-chain fatty acids or their esters, is better because even without proteins it has spontaneously formed aqueous nanochannels, lower electric resistance, and ionic selectivity [5]. Mobile quinones can transfer electrons through these membranes, but this redox process is electrically silent and there is no charge separation because of the co-transport of H^+- ions. As a result, the chemical reaction between two non-mixed substances does not stop [6]. The reaction products are also separated. Potentially it should make further production and purification of redox products much simpler, which is a biological principle known as membrane-based compartmentalization, but it does not lead to essential transmembrane voltage.

Later we used dense membranes made of H^+-doped polyaniline, known as synthetic metal [7]. In this case, it was possible to observe an electrogenic electron transport from ascorbic acid to the separated by the membrane ferricyanide. Transmembrane electric potential difference was formed, and in optimal conditions without permeating Cl^- it was described by the ideal Nernst equation [8]. In the presence of high Cl^- concentration the process was electrically silent, and no transmembrane voltage was formed. Instead, we had coupled counter-transport of electrons in exchange for chloride.

Though these membranes are easy to make and have low resistance, they are brittle. To make a system attractive for practical applications we tried simple metal foils separating in a chamber two aqueous solutions with different redox pairs and discovered that the foils behave like polyaniline membranes, i.e., they serve as membranes, ideally selective for electrons.

The purpose of this paper is to describe a new voltage-generating system based on metal foils and membrane biomimetic ideas. It does not have traditional anode and cathode, but instead of two electrodes and an ion-conducting solution between them it gives redox-based voltage through a not brittle metal foil separating two redox-active aqueous solutions. As a result, a new type of flow-through battery is suggested, where electrochemical cells in the battery are connected by ion-conducting membranes and not by external wires. The battery has low electric resistance and continuously gives reasonable current, which is different to biological membranes with protein-based ionic channels fluctuating between open and close states with characteristic time in a ms range.

II. Materials and Methods

The battery was assembled as a series of flow-through compartments separated by foils and ion-exchange membranes. Each compartment with the foil on one side and ion-exchange Nafion membrane on another side had an inlet and outlet tubes, so that both reducing and oxidizing solutions may be easily renewed, as it is done in redox-flow batteries (Figures 1, 2). Thus, each combination ion-exchange membrane/ solution 1/foil/ solution 2 /ion-exchange membrane forms a new type of electrochemical cell. To increase the ionic conductivity of the system aqueous solutions had 0.1M or 1M KCl. Ion-exchange membranes have two functions. They separate one cell from another, but simultaneously act as classical salt bridges providing due to ion permeability an electric connection between these cells. In aqueous solutions instead of expensive Nafion membrane we could use ion-exchange membranes Fumasep. The complete system was fixed by screws between two plastic plates.

The total voltage generated by the battery was measured between two covered by Ag/AgCl current collector plates, one in the very first and another - in the very last compartments. Current collectors are a pair of similar electrodes of the second kind with the equilibrium potential being a function of the concentration of an anion in the solution. These pairs do not necessarily lead to additional changes in an open circuit voltage. Instead, they convert ionic current in compartments into an electron-based current outside the battery and are also used for connection to the external load.

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The essential difference between metal foils and electrodes is that the foils are not connected by a wire one to another or to anything outside the electrochemical cell. The construction of an assembled battery allowed measuring not only electric potential difference between Ag/AgCl current collector electrodes in different solutions, but also the potential difference between a foil with a free tongue and a reference electrode. To do this the inlet and outlet tubes in each cell related to the capillary Ag/AgCl reference electrodes.

III. Results

When one foil separates two compartments with different redox solutions, it is possible to observe the difference in electric potentials between these solutions. This was demonstrated with different metal foils, including Cu, stainless steel, and Ag-plated Ni foils. Oxidants were ferricyanide, ceric (+4) ammonium nitrate, and hypochlorite. Reducing agents were ferrocyanide, sodium thiosulfate, and hydrazine in 0.1M KOH. In all cases, the difference of electric potentials in the oxidant solution versus the reducing solution was negative, as it should be according to the direction of electron transport through the foil from the electron donor to the acceptor.

A more detailed description of an experiment with a redox system hydrazine and hypochlorite ClO^- will make the difference with traditional systems more evident. Hydrazine reaction in alkaline media is $N_2H_2 + 4OH^- \rightarrow N_2 + 4H_2O + 4e^-$ and hydrazine fuel cells were studied since the 1970s [9]. Zero emission of CO_2 to the atmosphere makes them especially attractive. To avoid corrosion the 100 μ foils were made of titanium covered on both sides by a thin layer of catalyst. This catalyst was deposited from Pt chloride solution with heating at 250 ^{0}C. In our initial experiments the whole chamber was separated into four compartments by a sequence of a metal foil, a Nafion ion exchange membrane, and a second metal foil. The first and then the third compartment were filled with the same reducing solution of 2% hydrazine. The second and then the fourth compartments were filled with an aqueous solution of usual 7.5% bleach diluted to 2.5% and pH adjusted to 6.7 with NaH_2PO_4.

Redox potentials E_1 and E_2 of solutions were measured with Pt wire electrodes versus reference Ag/AgCl, and they were -0.72V for hydrazine solution and +1.07V for diluted bleach. When initially only the first compartment was filled with hydrazine solution, the potential difference titanium foil minus reference electrode ($\Delta\psi_1$) was -0.68V, near to that with Pt. When both the first and the second compartments were filled, it slowly drifted to -0.57V. The potential difference the reference electrode in the second solution minus the same foil ($\Delta\psi_2$) was equal to -1.05V, again near to redox potential measured in this solution with Pt. As expected, measured with two Ag/AgCl electrodes total voltage between the oxidant and reducing solutions was -1.62V. The foil is highly electroconductive and measured with millivoltmeter difference of electric potentials between the two sides of the foil $\psi_{f2} - \psi_{f1}$ was always zero. Because of this, the difference in electric potentials between two separated by the foil solutions is Its sign corresponds to electron penetration from the reducing donor to the oxidizing acceptor solution.

$$\Delta\psi_{2-1} = (\psi_{f1} - \psi_1) + (\psi_{f2} - \psi_{f1}) + (\psi_2 - \psi_{f2}) = \psi_2 - \psi_1 = -E_2 + E_1$$

The electric capacitance of the aqueous phase is much less than that of the metal foil. As a result, interfacial electron transfer leads to changes in electric potential in the aqueous phase, which should be added to the standard redox potential E_0. The stronger a reducing agent is, the more negative its redox potential is, resulting in more positive its final electric potential. When we slightly changed the composition and the redox potential of one solution, it changed its electric potential ψ, but not the electric potential of another solution with constant composition.

The structure with an ion-exchange membrane or even a wall on one side and the second membrane on another side with the metal foil between them forms a new type of elementary electrochemical cell with the difference in electric potentials between the two solutions. The cells can be assembled into a battery. To demonstrate this, we also filled the third compartment with a reducing solution. Using two Ag/AgCl electrodes we measured $\Delta\psi_{3-2}$ between this second reducing phase and the first oxidant solution separated from it by an ion-exchange membrane. As expected, the difference determined by the diffusion of ions through the membrane was rather small (0.045V). This also means that now the electric potentials of two reducing solutions (compartments one and three) are different, and a lower potential is in the third compartment.

Then we filled the fourth, i.e., the last compartment of the second electrochemical cell with an oxidant. The voltage difference between the oxidant compartment and the reducing compartment in the second cell was -1.7V, i.e., similar to -1.62V above. Not surprisingly, $\Delta\psi$ of the complete system, measured with Ag/AgCl electrodes between the first reducing and the last oxidizing solution, was -3.3V, i.e., the total of the voltages in the first and the second cells. Now we have a battery with new types of two electrochemical cells connected in series, and the electric potential difference

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from one reducing solution to another of the same type changes in a staircase manner. Note that the system had only one "classical" electrochemical cell, where the first foil, which reacts with an oxidant ClO^-, may be considered as a cathode, and the second foil, which reacts with a reducing agent, is similar to an anode.

In the next experiment we have added one more compartment formed by a metal foil and ion-exchange membrane at the beginning, and another similar compartment with a membrane and foil at the end of the chamber. Now the chamber has four foils total. The new, "zero", compartment was filled with an oxidant, which was separated from a reducing agent by the membrane. The new, fifth, compartment was filled with a reducing agent. In this case total voltage between the zeroth and fifth solution was near -4.5V, i.e., near -1.5V per cell. It decreased with time because of chemical reactions of hydrazine and the formation of nitrogen, but it was possible to recover the initial value by pumping a fresh solution into the chamber as it is done in redox flow cells. A video of LED and a small motor driven by this battery is available on demand.

When voltage between solutions in the oxidant (initially the second) compartment and the reducing (initially the first) compartment in the second cell was -1.7V, the electric current between two short-circuited metal foils was -170 mA (near 10 mA/cm^2). Thus, the specific power from one cell was 17mW/cm^2. Evidently, electric resistance was 10Ω or 170 Ωxcm^2. In comparison, recently described an electric eel-inspired power source, based on ion gradients between polyacrylamide hydrogel compartments bounded by a sequence of cation- and anion-selective membranes had only 27 mW per square meter per one cell [10].

IV. Discussion

One could say that now we have classical electrochemical cells in series where one surface of each foil serves as an anode in one cell and another surface of the same foil serves as a cathode in the next cell. This interpretation is different to the starting from Volta situation where two electrodes in electrochemical cell are separated by an electrolyte with ionic conductivity. Moreover, in addition to ionic conductivity of an electrolyte in a classical electrochemical cell, in the new electrochemical cell there is a step with electron-based conductivity. Electrons are moving through the foil from a surface in contact with a reducing agent to a surface in contact with an oxidant. This leads to charge separation and the formation of a difference in electric potentials between these two solutions.

If the reducing agent is in the left solution, and an oxidant is in the right solution, electrons are transferred from the left to the right solution through the foil, i.e., counterclockwise in the circuit. In comparison, when the standard electrochemical cell is discharged, the reducing agent in the left solution reacts with an anode; electrons are transferred to this anode and then they flow outside the cell clockwise. Only then do they reach the oxidant solution via cathode. To have the whole circuit electrically neutral usually it is a proton in acidic media, which is transferred through an ion-selective membrane in a solution counterclockwise.

When a reducing agent (donor of electrons) is in the left, and an oxidant (electron acceptor) is in the right half-cell, the traditional redox electrode on the left side (anode) has an electric potential more negative in comparison to the cathode in the right side, i.e., $\Delta\psi = \psi_{right} - \psi_{left} > 0$. Experiment shows that the electric potential in the right solution becomes more negative than in the left solution, i.e., $\Delta\psi = \psi_{right} - \psi_{left} < 0$, similar to presented above $\Delta\psi_{2-1} = \psi_2 - \psi_1 = -E_2 + E_1$. Thus, the sign of $\Delta\psi$ is opposite to traditional systems, which is explained by the fundamental difference of underlying mechanisms. To have the same sign in the traditional system the very first compartment should have an oxidant in it. Note that one cannot switch positions of an anode and cathode simply because the anode will become a cathode giving electrons and *vice versa*. Classical electrochemical cells and the cells in our case may look similar, but they are different just like left-hand and right-hand gloves.

To measure the difference in potentials between two aqueous solutions separated by the foil we used two additional reference electrodes. Measured on a battery with Ag/AgCl electrodes total potential difference was formed between the first (reducing) and the last (oxidant) solutions, and it is not the total of potential differences between two electrodes (anode and cathode) as it is in a classical battery.

Based on construction, most similar to the presented here system are so-called bipolar accumulators where a cathode of one cell is connected to an anode of the second cell instead of wires via metal foils, separating one cell from another. See, for example, an old patent [11] of P. Kapitza, who later became a Noble Prize laureate in physics, and a recent patent by D. Mourzagh, et al. [12]. If the battery has two elements connected by the bipolar plate, it has two electrodes and one ion-exchange membrane in the first element, two more electrodes and the membrane in the second element, plus a bipolar plate between the elements. In comparison, a new system has only one ion exchange membrane and two foils. Foils are not electronically interconnected one with another, which is also different from electrodes in different electrochemical cells in a battery. Instead, the cells are connected via ion-exchange membranes. Finally, all we need is two current collectors, which is especially advantageous for a battery with many cells.

Though described battery has a lot of similarities with traditional batteries, it also has a lot in common with membrane-based systems (Figure 2). Similarly, redox reactions are taking place on two interfaces of chloroplasts, mitochondrial and microsomal membranes in biology, but based on accepted terminology we would not say that our body is filled with electrodes. Of course, there are two coupled redox processes on different surfaces of the foil, but the foil is neither an anode nor a cathode.

The advantage of electrodes is that they may have a very large and developed surface area, thus increasing exchange currents. The disadvantage is that the cells with electrodes are much thicker and heavier. An efficient catalyst immobilized on the foil surface should decrease electrochemical resistance. For example, an exchange current density *i* is near 10^{-12} A/ cm^2 with Hg electrodes, and it may be as high as 10^{-3} A/cm^2 with Pt. Biology has chosen this path, using, for example, cytochrome oxidase and catalase, which is one of the most catalytically active membrane-based enzymes.

Note also that each foil cannot be described based on traditional models of membrane electrochemistry. Classical nonbiological membranes are thick, so that the interface processes are relatively fast and transport through the membrane is the rate-limiting step. With foils two slow redox reactions are at the surfaces, and they are the rate-limiting steps. If the foil is polarizable, when incoming through the first interface current is equal to outgoing through the second surface, i.e., $i = const = (\overrightarrow{i}_1 - \overleftarrow{i}_1) = (\overrightarrow{i}_2 - \overleftarrow{i}_2)$, the process can be described based on Butler-Volmer expressions [13]:

$$-k_{01}F\{\exp[\alpha_{r1}\frac{F}{RT}(\psi_{f1}-E_1^0)]c_{r1}-\exp[-\alpha_{o1}\frac{F}{RT}(\psi_{f1}-E_1^0)c_{o1}\} =$$
$$-k_{02}F\{\exp[-\alpha_{o2}\frac{F}{RT}(\psi_{f2}-E_2^0)]c_{o2}-\exp[\alpha_{r2}\frac{F}{RT}(\psi_{f2}-E_2^0)]c_{r2}\} \quad (3)$$

Asymmetry coefficients are mutually related, and $\alpha_r + \alpha_o = 1$. In equilibrium, for each of the redox pairs total current $i = 0$. Thus, only when each of the redox pairs is acting separately, this gives two familiar Nernst equations for an anode and cathode sides:

$$\psi_{f1} = E_1^0 + \frac{RT}{F}\ln\frac{c_{o1}}{c_{r1}}$$
$$\psi_{f2} = E_2^0 + \frac{RT}{F}\ln\frac{c_{o2}}{c_{r2}} \quad (4)$$

Without equilibrium $\psi_{f1} = \psi_{f2} = \psi_f$ because of high conductivity of the foil. Further, in a practically interesting situation with only a reducing agent in the first and only an oxidant in the second solution in the steady-state

$$-k_{01}F\exp[\alpha_{r1}\frac{F}{RT}(\psi_f - E_1^0)]c_{r1} = -k_{02}F\exp[-\alpha_{o2}\frac{F}{RT}(\psi_f - E_2^0)]c_{o2} \quad (5)$$

After simplification it gives

$$\psi_f = \frac{1}{\alpha_{r1}+\alpha_{o2}}(\alpha_{r1}E_1^0 + \alpha_{o2}E_2^0 + \frac{RT}{F}\ln\frac{k_{02}c_{o2}}{k_{01}c_{r1}}) \quad (6)$$

This equation is more general than the Nernst equation. It describes the electric potential of a foil as a function of electrochemical properties and concentrations of components of both redox pairs and it is different to a traditional battery description. The foil potential ψ_f may be somewhere between two standard potentials, $E_1^0 < \psi_f < E_2^0$. Similarly, corrosion for electrodes dipped into one solution with two redox pairs leads to mixed potentials [13].

Thinking about applications, we can make a few simple estimates. Assume that the transmembrane voltage is 1V, and the specific resistance is 1 Ωxcm^2. Both are realistic numbers. This gives an electric current of 1A/cm^2, and the power per area is 1 Watt/cm^2. With a stack of foils 10x10 cm^2 each, the power will be enough to light an incandescent 100-Watt bulb in a room. To have 1 Megawatt we need a total 10^6 cm^2 of membrane area or 100 m^2. If the foils are packed in parallel and the foil plus solution thickness is 100 micron (10^{-4} m), the volume we need is only 10^{-2} m^3, i.e., only 10 L. Other obvious applications are power banks to charge *i*-phones and tablets, battery chargers, car, motorcycles, and especially boat starter (cranking) battery.

Weight is important for many applications. We can assume that 1 kg of a solid oxidant has 10 moles of salt, and each molecule accepts 8 electrons, as it is for $NaClO_4$ reduced into Cl^-. In this case the total charge transferred is $8\times10^6 Q/kg$ or 2200 *Ah/kg*. If the transmembrane voltage is 1 V, this should give energy near 2200 *Wh* per kg of solid phase, which is much better than it is for advanced redox fuel cells. Well-known lithium batteries with lithium iron phosphate cathode have energy density of about 160*Wh*/kg. 12V battery of this type with dimensions 11.42 x 7.87 x 7.87 inches, weight 26 lbs, and the price near $500 gives 100*Ah.*

Traditional batteries with N electrochemical cells should have 2N electrodes, connected in series from one cell to another. Presented here redox flow battery will have only N mutually nonconnected foils, which makes a battery assembly simpler, and two current collecting electrodes necessary to convert ionic current to electronic current in the very first and very last cell. It is possible that with time one of the current-collecting electrodes (not necessarily Ag/AgCl) will be practically dissolved. After that it is possible simply to switch positions of reducing and oxidant solutions, thus reversing the electrochemical processes on electrodes.

Batteries and fuel cells are not subject to the Carnot cycle limitations, they may operate with much higher efficiencies than combustion engines and will be comparable to biological energy-converting membranes. The ancillary equipment to operate the device can be a simple pump with channels to supply solutions of reducing and oxidizing agent. The energy necessary for these steps is much less than the chemical energy generated by the cell, which should lead to high energy conversion efficiency. The suggested fuel cell system will be very volume- and energy-efficient. It does not need strong acids and may be easily recharged at home. It will be smaller, lighter, cheaper, and more environmentally benign than existing vanadium-based redox flow batteries [14].

We hope that this paper will also help a more fundamental understanding of the principles and definitions used in the description of electrochemical electrodes, membranes, cells, and batteries [15].

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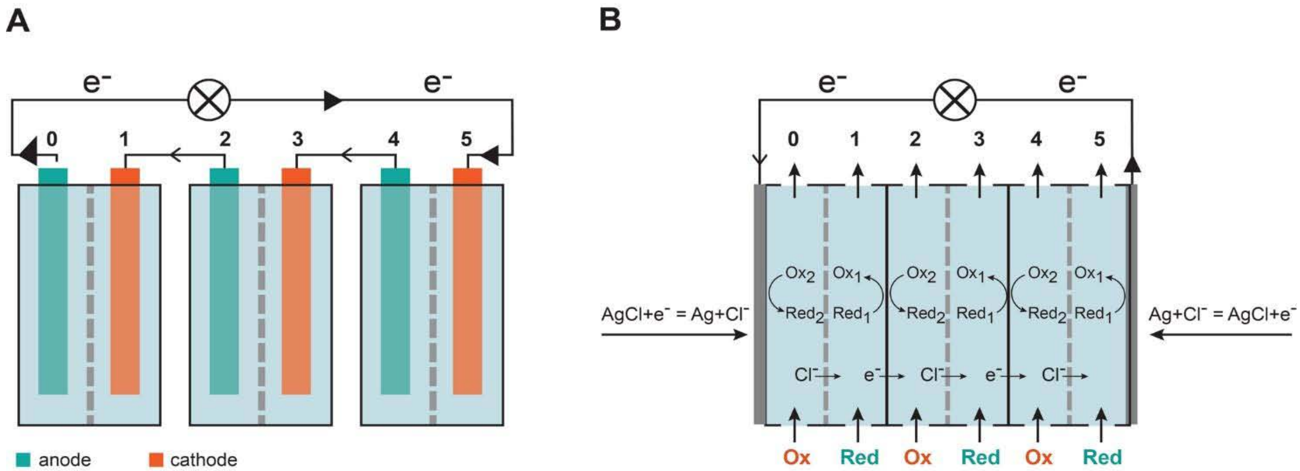

Figure 1: Comparison of electrochemical cells in electrode-based and foil-based redox-flow batteries.

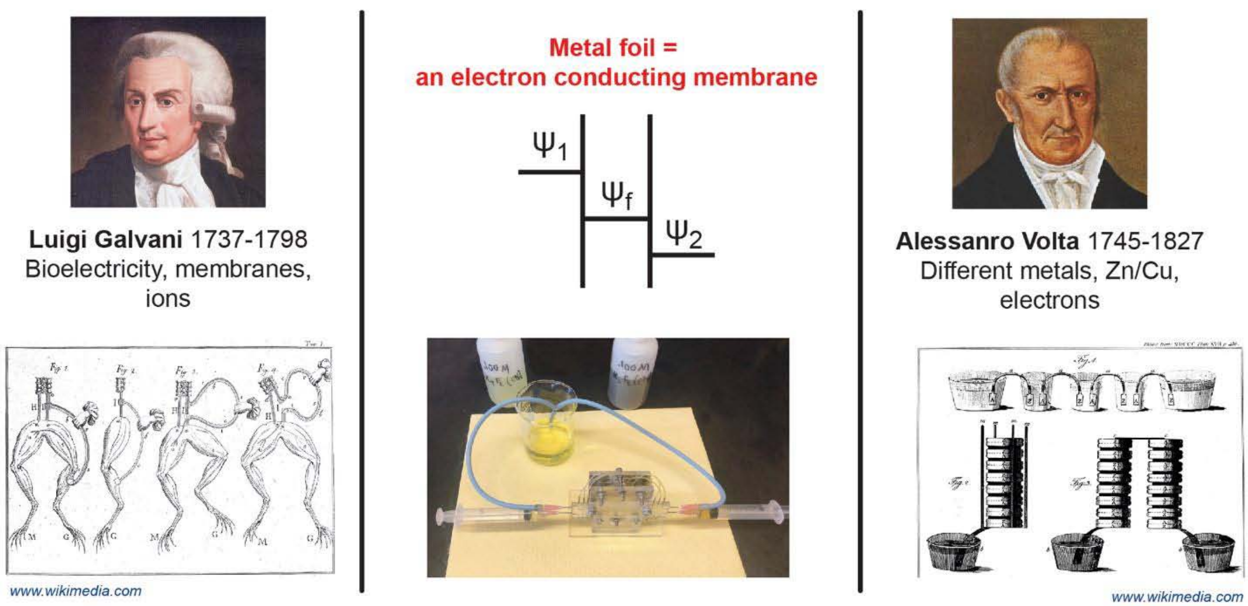

Figure 2: Three different principles of conversion of chemical energy to electrical.

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Promoting Health and Safety Practices in Fast- Track Construction Projects: The Case of Jordan

By Zayed Zeadat

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This research aims to assist Jordanian construction consultants and contractors in determining the best policy for promoting health and safety in fast-track construction projects. Data was collected using a questionnaire distributed to consultants and contractors; the data was then analyzed using the Relative Importance Index (RRI). The findings and discussions reveal two essential policies to facilitate CSSM in Jordan's fast-track construction projects.

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This research aims to assist Jordanian construction consultants and contractors in determining the best policy for promoting health and safety in fast-track construction projects. Data was collected using a questionnaire distributed to consultants and contractors; the data was then analyzed using the Relative Importance Index (RRI). The findings and discussions reveal two essential policies to facilitate CSSM in Jordan's fast-track construction projects. 1) The provision of a first aid box, which is a critical component that is frequently associated with ensuring the construction industry's safety. 2) Communicating health and safety, which enhances safety awareness and reduces the number of accidents and associated costs. The research analysis also affirmed that the two least important policies, according to respondents, were 1) Workers' participation in hazard identification on sites and 2) recruiting outside health and safety consultants. This policy requires employing an organization or individuals with the necessary knowledge, experience, and ability to oversee health and safety on construction projects.

I. Introduction

The fast-track construction sector has long been recognized as one of the most dangerous economic activities in many parts of the world (Chi et al., 2005; Tam et al., 2004; Jaselskis et al., 1996). The fast-track construction industry's abysmal safety record generates widespread concern (Haslam et al., 2004). This is reasonable considering that fast-track construction has the highest death rate of any industry (López et al., 2008; Behm, 2005). According to statistics, construction workers are three to four times more likely than other workers to die in a fast-track construction site (Umar et al., 2017). At least 108,000 people are fatally killed on fast-track construction sites each year, accounting for over 30 percent of all fatal occupational injuries (Gürcanli and Müngen, 2013).

Author: e-mail: z.zeadat@aum.edu.jo

The concept of safety culture is gaining traction due to its capacity to encompass all perceptional, psychological, behavioral, and management variables (Rafiq *et al.,* 2007). Numerous scholars have studied factors that improve health and safety in the fast-track construction industry in different cultural contexts (Cheng et al., 2010; Im et al., 2009; Cameron et al., 2008; Macedoand Silva, 2005; Mungen and Gürcanli, 2005; Etiler et al., 2004). According to Tam and colleagues (2004), various factors influence fast-track construction industry safety performance. This includes workers' attitudes (Hinze, 1981); the size of the company, adopted safety policy, project organization, and economic pressure (Hinze and Raboud, 1988); safety management training (Gun, 1993; Jaselskis and Suazo, 1994); and safety culture (Tam and Fung, 1998; Glendon and Stanton, 2000; Tam *et al.,* 2001).

Regardless of these factors, fast-track construction companies that demonstrate and convey their commitment to well-structured and well-funded safety initiatives can significantly reduce incident rates (Hinze, 1997). Fast-track construction safety management has dramatically improved following the Occupational Safety and Health Act enacted in 1970. President Richard Nixon signed the Act, which granted the US Federal Government the power to define and enforce safety and health standards for most of the country's employees. Also, the Act made the employer (i.e., fast-track construction companies) responsible for implementing safety principles in the fast-track construction industry and has resulted in a significant increase in safety planning and management in the fast-track construction industry at large (Hill, 2004)

II. Health and Saftey in Jordan's Fast-Track Fast-Track Construction Projects

Fast-track construction projects play a significant role in the global economy; there is massive pressure to manage project duration while meeting legal requirements, emergency/disaster recovery, and time-to-market constraints. As a result, traditional fast-track construction planning can be compressed using some techniques, such as fast-track projects (Garrido Martins *et al.,* 2017). Fast-track construction is commonly described as the overlapping and compressing of multiple operations in the conceptual design,

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procurement, and fast-track construction phases to accomplish a project rapidly and cost-effectively (Cho et al., 2010). Fast-track construction allows for overcoming the sector's current high fast-track construction costs and inflation challenges. In the fast-track construction and engineering sectors, the fast-track technique utilizes the capacity to efficiently overlap and manage activities in the design, procurement, and fast-track construction phases concurrently to shorten the expected project schedule.

Although the fast-track project delivery approach has several advantages, such as accelerated project completion and lower operating costs (Aleshin, 2001), existing research has identified several challenges that may impede the success of fast-track projects. Harthi (2015) identified client, consultant, and contractor changes, technological changes, safety considerations, a shortage of skills, and a lack of equipment as barriers to fast-tracking a project. Inadequate planning also leads to significant changes in scope and, as a result, project cost overruns. Most importantly, compressing the schedule increases project complexity and introduces new risks, which frequently occur due to overlap between project phases and the risk-management strategies employed by project teams (Aleshin, 2001). The consequences of these risks are perceived in terms of schedule, cost, and technical performance (Harthi, 2015) and can lead to health and safety issues in fast-track projects. This global impact can lead to an increase in the pace of the work sequence, which can exacerbate preconditions and lead to quality and safety failures (Garrett and Teizer, 2009).

Harthi (2015) proposed methods and strategies to control the risk associated with severe compression of project timelines while still guaranteeing project quality meets health and safety standards. He concluded that when dealing with fast-track projects, fast-track construction practitioners should focus on modifying the organizational structure to ensure flexibility, effective communication, and risk management is executed in all concurrent processes. Fast-tracking necessitates that safety risks are clearly defined and constantly monitored throughout the project and that feedback is provided as soon as possible to ensure that health and safety measures are implemented instantly. He also acknowledged the need for managers to receive training, education, and awareness, in which the training/education sessions introduce them to various risk mitigation models and allow them to test and implement the most convenient policy.

Fast-tracking is a more prevalent delivery method in the Middle East (Mehran, 2016) and Jordan. An example of a fast-track construction project in Jordan is The King Hussein Convention Center[1]. This project is Jordan's largest convention center, located next to the seashore of the Dead Sea, and has a total buildup area of 28,000 m^2. The project's fast-track construction started on 01-10-2003 and was finished on 10-05-2004 in preparation for the Annual World Economic Forum to be held in Jordan.; a total of 1,200 people were hired to work for 24 hours a day to complete the project in 6 months (Haddadinco, 2020).

Like many other developing nations, Jordan's culture and economy have incurred human and financial damage due to the poor Fast-track construction Site Safety Management (CSSM) (El-Mashaleh *et al.,* 2010). A study conducted in Jordan by (El-Mashaleh et al., 2010) revealed that annual data issued by the Ministry of Labor (1995-2005) show that the number of work accidents in all industries has continued to rise at alarming rates. Despite accounting for about 7.1 percent of the labor force, the Occupational Safety and Health Institute (OSHI) in Jordan states that accidents in the fast-track construction industry account for approximately 10.5 percent of incidences (OSHI, 2006). However, the actual percentage is approximately 17% (Assbeihat, 2015). According to Hiyasat and Talhuni (2000), the number is much higher for various reasons: several companies avoid reporting injuries on their sites, while others seek to avoid facing the costs of penalties for non-compliance with the terms of the application of public health and safety regulations. Additionally, tens of thousands of workers are employed unofficially in small firms with no social security membership.

The fast-track construction industry is an essential aspect of Jordan's infrastructure development and contributes significantly to the country's economy (Alubaid et al., 2020; Alkilani *et al.,* 2012). Jordanian scholars argued that the country's low economic structure contributes to a lack of health care and professional treatments available to the labor structure (Al-Smadi, Supeni, and Voon, 2021). A study conducted by Alkilani and colleagues (2013) revealed that Jordan's CSSM and measurement are still in their infancy. The failure to implement regulations, policies, and legislation demonstrate a lack of government commitment, limiting the efficiency and productivity of government departments tasked with CSSM and impeding the development of effective CSSM practices.

III. Health and Safety Policies in the Fast-Track Construction Industry

Health and safety policies create broad and general duties on employers, employees, and the self-

[1] It consists of a ballroom for conferences that can accommodate up to 2400 people and ten meeting rooms of various large sizes that can accommodate up to 4,000 people. The structure also includes a 3000 m2 Royal Wing with meeting rooms, lounges, reception wings, and V.I.P. wings (Haddadinco, 2020).

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employed (Baxendale and Jones, 2000). It is the employers' foremost duty to ensure all employees' health, safety, and welfare (Hughes and Ferrett, 2008). These policies include commitments from the employer to choose competent personnel, establish emergency protocols, notify employees, and collaborate with other firms that share the same workplace. On the other hand, employees are also responsible for reporting harmful circumstances or flaws in health and safety procedures in fast-track construction sites (Health and Safety Executive, 2013). For instance, each construction worker ought to wear and use protective equipment. Personal Protective Equipment (PPE) keeps construction workers safe and mitigates the seriousness of injuries (Shazwan *et al.,* 2018). On fast-track construction sites, many PPEs are used, including safety equipment, protective clothing, impact-resistant clothing, full-body protective clothing, personal protection shield, and cleanroom suit (Ammad *et al.,* 2021). They also include protective clothing and equipment used as fast-track construction safety norms to reduce accidents. Using safety workwear is vital to promote CSSM, thus preventing—or reducing the impact of accidents. Because fast-track construction sites are typically located outside, seasonal variations have a significant impact, which necessitates the creation of workwear suitable for both summer and winter. In the summer, the employees' faces and heads need to be kept cool, while their hands and faces need to be kept warm in the winter (Eom and Lee, 2020).

Despite accident causation and prevention techniques, motivating and controlling workers to wear PPE needs efforts (Wong *et al.,* 2021). Employers may address the use of PPE in three trajectories (Kelm *et al.,* 2013): (1) education and training, (2) incentives, and (3) enforcement. PPE is generally seen as the most monotonous hardware in a construction worker's daily routine, but it is also regarded as the penultimate line of defense in any situation (Farooqui, 2009). PPE is typically overlooked in underdeveloped nations, although it is often the only line of defense against building site risks in developed countries (Ammad *et al.,* 2021).

Employers must ensure continuous accident reporting and follow-up in fast-track construction sites. Construction accident investigation procedures and reporting systems determine what kinds of accidents happen and how they happen (Abdelhamid and Everett, 2000). According to Ale and colleagues (2008), employers must report workplace accidents within 24 hours of their occurrence. Accident reporting enables strict implementation of safety policy on fast-track construction sites. According to Holt (2008), a safety policy is a document that should be available at every construction site. The following should be covered in the policy document:

- A firm commitment to providing a safe and healthy working environment in construction sites;
- An explicit declaration that reposting an accident will have no negative consequences on workers;
- A strict commitment to ensure appropriate funding and facilities are available to ensure the policy's success
- The responsibility of all construction workers to abide by relevant legal regulations;
- Measure to promote staff awareness of safety policy.

The Safety policy document should be reviewed and checked regularly by a senior project manager. Unfortunately, a study conducted in Jordan concluded that 66% of Jordanian fast-track construction firms fall short of international standards, and 43% lack any standard guidelines for safety policy (Alubaid et al., 2020). Moreover, it has been observed by the author that the vast majority of construction sites in Jordan lack adequate safety welfare facilities. According to the International Labor Organization (ILO), there are eight distinct categories of welfare facilities. These are; sanitary facilities, washing facilities, facilities for supplying food and drink, and eating meals. Other scholars added facilities for changing, storing, and drying clothes and rest breaks (Abba *et al.,* 2019). Before any fast-track construction activity (including demolition) begins, the availability of welfare facilities, their placement on-site, and regular checkups must be addressed throughout the planning and preparatory stages of the project. When planning welfare provisions for fast-track construction sites, site engineers ought to consider the nature of the work to be done, as well as the health risks associated with shower provision where the project involves dealing with very dirty work (for example, sewer maintenance, dusty demolition activities, contaminated land work, or concrete pouring (Tabi and Adinyira, 2018).

The demand for safety awareness among fast-track construction organizations has risen considerably during the last decade. Pheng and Shiua (2000) emphasized that quality and safety should be integrated to achieve better coordination and utilization of resources. Koehn and Datta (2003) revealed that adopting safety rules and regulations could help address poor quality work, unsafe working conditions, and a lack of environmental control. The high expense of work-related injuries, workers' compensation, insurance premiums, indirect costs of injuries, and litigation contribute to project failure. A significant amount of time is wasted every year due to work-related health issues and site accidents; therefore, quality and safety are critical in the fast-track construction industry (Shamsuddin *et al.,* 2015). One example of a measure to improve the safety of fast-track construction work is the installation of safety signs (Arphorn *et al.,* 2003). It is imperative that safety signs are well-designed and understood to alert both trained and untrained people about possible hazards and provide clear instructions on minimizing or eliminating accidents and dangerous conditions (Chan and Chan, 2011). There are many different types of warnings, including vocals, bells, and beep sounds. Warning labels are one of the most popular signs used in the fast-track construction sector. They provide alerts and necessary information informing observers what is permissible and forbidden. Typically, a warning label contains four parts: signal words like "caution," a danger statement, a statement advising observers what will happen if they do not comply, and a statement informing observers how to avoid the hazard. The primary goal is to call attention to the situation and send out immediate warnings about the danger level (Tam *et al.,* 2003).

Safety signs are imperative for identifying and clarifying hazardous activities in fast-track construction sites. The more simultaneous construction activities in fast-track construction projects rise, the more health and safety risks arise. This would become an urgent problem when engaging untrained, unskilled workers to complete the job quickly and feasibly (Ramteke *et al.,* 2021). For instance, workers in hazardous construction activities that include handling hazardous materials (i.e., toxic and chemical wastes) should receive proper training, adequate information on the substances they will be handling, and appropriate protective equipment. Other hazardous items, such as explosives, flammable liquids, and corrosive and acidic compounds, require special training and attention (Teo *et al.,* 2005). It is impossible to keep track of all the potentially dangerous activities on a fast-track construction site. As a result, hazardous operations with higher risks should be recognized and prioritized ahead of time so that senior management can proactively handle them (Song *et al.,* 2007). Therefore, consultants, contractors, and project managers should frequently meet to co-create and develop new safety measures, provide feedback to one another, and address safety-related concerns (Maki, 2015). Periodic site meetings to ensure health and safety are necessary communication tools to share safety information among critical stakeholders in construction (Tam *et al.,* 2004). Jaselisks and colleagues (1996) advocate increasing the number of formal safety meetings with site project managers to enhance project safety performance.

Consequently, fast-track construction sites with superior safety performance had more safety-related meetings than companies with poor safety performance. Both sorts of meetings ("toolbox" safety talks and project-level safety meetings) are clear signs of a company's attention to the significance of safety. Unfortunately, only one percent of construction projects in Jordan have regular safety meetings at the project level (Mashaleh et al., 2010). This indicates poor health and safety awareness among workers and senior management. Construction workers' awareness makes a considerable contribution to project success. To address these present difficulties, project managers should prioritize worker safety and well-being (Ogundipe et al., 2018; Akinwale and Olusanya, 2016).

Many fast-track construction projects require the appointment of a health and safety officer. Safety officers are responsible for carrying out the self-inspection program and ensuring that adequate safety performance is attained through appropriate methods (Langford et al., 2000; Koehn *et al.,* 1995). Principal contractors hire them for large projects to manage all safety issues on the fast-track construction site (Teo (2005; Wilson and Koehn, 2000). Therefore, it is essential for safety officers to understand and determine types and complex construction activities in a fast-track construction. Safety officers must be well-trained and experienced in dealing with the various safety risks during fast-track construction activities. A fundamental prerequisite for a safety officer is to be vigilant, diligent and informed to supervise the daily activities and fast-track construction projects (Hinze and Wilson, 2000). Due to the complexity of fast-track construction projects, some scholars recommend hiring health and safety consultants. According to Oloke and McAleenan (2017), safety consultants are professional firms vested in overseeing fast-track construction sites' health and safety. They can be an organization or individuals with sufficient knowledge, experience, and ability to handle complex, fast-track construction projects. During the pre-construction phase of a project, they plan, manage, monitor, and coordinate health and safety. This involves detecting, removing, or managing potential hazards and ensuring that designers fulfill their responsibilities. They also prepare and provide relevant information to other stakeholders, particularly the contractor (or principal contractor), to help them plan, monitor, and coordinate health and safety in the fast-track construction phase.

Construction workers' participation in CSSM is widely discussed in the literature. For instance, workers could be engaged in identifying hazardous activities in fast-track construction projects. Identifying safety hazards is a critical step in reducing non-fatal fall injuries and enhancing the safety performance of fast-track construction projects. Current safety hazard identification methods rely on experts' judgment to identify risks and as a result, they are unable to comprehensively detect dangers in the diverse and dynamic character of the fast-track construction environment (Antwi-Afari *et al.,* 2020; Reese and Eidson, 2006). One of the most challenging aspects of CSSM for fast-track construction sites is ensuring that workers can anticipate, detect, and respond to potentially dangerous conditions before being exposed to them.

To sum up, Table 1 below depicts the most common CSSM policies identified in the literature.

Barrier	Description	Reference(s)
Provision of Personal Protective Equipment (PPE)	(PPE) keeps people who work on construction sites safe. It Includes safety equipment, protective clothing, impact-resistant clothing, full-body protective clothing, personal protection shield, and a cleanroom suit	(Shazwan et al., 2018). (Ammad et al., 2021).
Accident Reporting and Maintenance Report	Construction accident investigation procedures and reporting systems determine what kinds of accidents happen and how they happen. Employers are required to report workplace accidents within 24 hours of their occurrence.	(Abdelhamid and Everett, 2000). (Ale et al., 2008).
Provision of Safety Policy	The safety policy is the core document in the management of safety. The general statement of policy should include an expression of the employer's intentions, rather than relying just on employees' safe behavior.	(Holt, 2008).
Provision of Adequate Welfare Facilities on Site	Before any construction activity begins, the availability of welfare facilities must be addressed throughout the planning and preparatory stages of the project. The welfare facilities categories are sanitary facilities, washing facilities, facilities for supplying food and drink, eating meals, and facilities for changing, storing, drying clothes, and rest breaks.	(Tabi and Adinyira, 2018). The International Labor Organization (ILO).
Provision of Health and Safety Clothing and Equipment	Protective clothing and equipment should be used as part of construction safety norms to reduce accidents. The use of safety equipment/clothing is a suitable safety procedure likely to prevent or reduce the impact of accidents.	(Langford et al., 2000).
Provision of a Healthy and Safe Working Environment	The industry seeks high quality while also guaranteeing a safe working environment; therefore, adopting safety rules and regulations could help address poor quality work, unsafe working conditions, and a lack of environmental control.	Pheng and Shiua, 2000). (Koehn and Datta, 2003)
Provision of Health and Safety Signs	safety signs are well designed and understood to alert both trained and untrained people about possible hazards and provide clear instructions on minimizing or eliminating accidents and dangerous conditions.	(Chan and Chan, 2011).
Control of Hazardous Activities on the construction site	It is impossible to keep track of all the potentially dangerous activities on a construction site. As a result, hazardous operations with higher risks should be recognized and prioritized ahead of time so that engineers and management can safely handle them.	(Song et al., 2007).
Site Meetings Especially for Safety Purposes	Consultants, contractors, and project managers should frequently meet to co-create and develop new safety measures, provide feedback to one another, and address safety-related concerns. Regular safety meetings are one type of site meeting; they are necessary for communicating safety information to all parties.	(Maki, 2015). (Tam et al., 2004).

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Ensuring Health and Safety Education	Increased awareness of the importance of occupational health and safety and training on identifying and managing risk among contractors and workers will improve site safety.	(Akinwale and Olusanya, 2016).
Designated Health and Safety Person	Safety officers are responsible for carrying out the self-inspection program and ensuring that adequate safety performance is attained through the use of appropriate methods	(Koehn et al., 1995).
Communicating Health and Safety	Safety communications should be integrated with current quality and environmental systems. An integrated system should boost staff morale; promote employee participation in safe behaviors, and lower incident rates.	(Weinstein 1996).
Provision of First Aid Box	First aid box is a critical component that is frequently connected with ensuring the construction industry's safety. The nature and scope of work, the number of employees, and, most all, the types of dangers that may arise should all be considered while providing first aid in the workplace	(Jędrzejas and Sobala, 2018).
Workers' Participation in Hazard Identification on Site	The identification of safety hazards is a critical step in reducing injuries and enhancing the safety performance of construction workers, and it ensures that workers can anticipate, detect, and respond to potentially dangerous conditions before they are exposed.	(Antwi-Afari et al., 2020). (Chen et al., 2013).
Using Outside Health and Safety Consultants	Safety consultants are tasked with overseeing health and safety on construction sites. They can be an organization or individuals with sufficient knowledge, experience, and ability to carry out the role.	(Oloke and McAleenan, 2017).

IV. Materials and Methods

This research aims to help consultants and contractors in the Jordanian construction sector decide on the best policy for promoting health and safety in fast-track construction projects. To achieve meaningful and trustworthy research outcomes, this study uses quantitative and qualitative research and data-gathering methodologies. The authors undertook a thorough study of academic publications, textbooks, and peer-reviewed journals to identify the most frequent health and safety policies in the construction sector. However, policies and their efficacy vary depending on the context, and some of them may not apply in fast-track construction projects due to differences in operational and managerial characteristics. The fifteen policies extracted from the literature review were tabulated in a questionnaire style, and their applicability to the fast-track construction environment was assessed based on study participants' opinions and judgments. Purposive sampling was used to choose research respondents officially registered in the Jordan Engineering Association and the Contractor's Association. The respondents were asked to rate the acceptability of each policy on a scale of one to five according to the Likert scale. The questionnaire survey was disseminated by hard copy, email, Google forms, and in-person interviews. The following were the inclusion criteria employed in this study: Each research respondent should hold a bachelor's degree in a field related to construction, such as civil engineering, mechanical engineering, architectural engineering, or construction project management. This criterion guaranteed that the respondents were knowledgeable about construction management's technical components. The second requirement is that research participants have at least five years of experience working on fast-track construction projects. The third criterion is that research participants should be involved in inspecting and investigating on-site safety activities.

a) Relative Importance Index

After collecting survey data, responses from research participants were evaluated using the Relative Importance Index (RRI). RII is a non-parametric trustworthy approach used to analyze structured questionnaires with ordinal attitude assessment. The value and significance of RII reside in its capacity to determine how much a given variable contributes to the prediction of a criterion variable when used alone or in conjunction with other predictor variables. The RII for each incentive strategy was calculated using the following equation

$$RII = \frac{5(n5)+4(n4)+3(n3)+2(n2)+n1}{5(n1+n2+n3+n4+n5)} \quad (1)$$

Equation (1) is the Relative Importance Index Equation, where n1; n2; n3; n4; and n5 are the number of respondents who selected: 1, not effective; 2, for slightly effective; 3, for effective; 4, for very effective; and 5, for highly effective, respectively. Moreover, this study adopted the classification guide in [48, p.239] to determine the level of impact of RII for each driver. See Table III below:

Table 1: Classification Guide to Determine Importance Level of RII

RII score	Evaluation criteria
.200-.358	Very low level
.359-.518	Low level
.519-.678	Medium level
.679-.838	High level
.839-1.00	Very high level

b) Research validity and reliability

Cronbach's Alpha and Pearson's correlation coefficient test quantitative research reliability and validity, respectively. Cronbach's Alpha was used to determine the internal consistency of the returning sets. The alpha coefficient typically runs from 0 to 1, the higher the value, the more dependable the study [49]. To confirm the consistency and dependability of the data collected, a minimum value of 0.5 is used [49]. Cronbach's alpha (a) is calculated by (2) below, where *n* is the number of questions; *Vi* is the variance of scores on each question; and V_{test} is the total variance of the overall scores (Howitt & Cramer (2008) cited in [51, p.337]):

$$a = \frac{n}{n-1}\left(1 - \frac{\sum v_i}{v_{test}}\right)$$

Pearson's correlation (also called Pearson's R) is a correlation coefficient commonly used in linear regression. The correlation coefficient formulas are used to determine the strength of a relationship between two data sets. The formulas generate a number between -1 and 1, with (1) denoting a strong positive relationship, (-1) denoting a strong negative relationship, and zero denoting no relationship.

Reliability Statistics

Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	N of Items
.942	.943	15

The Cronbach Alpha coefficient was reported as 0.779. Accordingly, the current study reported an excellent Cronbach Alpha coefficient, thus ensuring the scale's internal consistency.

Correlations (N=194)		
		Total
VAR1	Pearson Correlation	.841
	Sig. (2-tailed)	.000
VAR2	Pearson Correlation	.784
	Sig. (2-tailed)	.000
VAR3	Pearson Correlation	.828
	Sig. (2-tailed)	.000
VAR4	Pearson Correlation	.823
	Sig. (2-tailed)	.000
VAR5	Pearson Correlation	.819
	Sig. (2-tailed)	.000
VAR6	Pearson Correlation	.786
	Sig. (2-tailed)	.000
VAR7	Pearson Correlation	.858
	Sig. (2-tailed)	.000
VAR8	Pearson Correlation	.746
	Sig. (2-tailed)	.000
VAR9	Pearson Correlation	.841
	Sig. (2-tailed)	.000

VAR10	Pearson Correlation	.807
	Sig. (2-tailed)	.000
VAR11	Pearson Correlation	.644
	Sig. (2-tailed)	.000
	N	194
VAR12	Pearson Correlation	.622
	Sig. (2-tailed)	.000
	N	194
VAR13	Pearson Correlation	.623
	Sig. (2-tailed)	.000
	N	194
VAR14	Pearson Correlation	.499
	Sig. (2-tailed)	.000
	N	194
VAR15	Pearson Correlation	.678
	Sig. (2-tailed)	.000
	N	194
	N	194

V. Results

Code	Variables (safety measures)	RII	Rank	Level of importance
VAR1	Provision of personal protective equipment	.8281	3	High level
VAR2	Accident reporting and maintenance report	.7645	7	High level
VAR3	Provision of safety policy	.7968	5	High level
VAR4	Provision of adequate welfare facilities on site	.7500	9	High level
VAR5	Provision of health and safety clothing and equipment	.7791	6	High level
VAR6	Provision of healthy and safe working environment	.7562	8	High level
VAR7	Provision of health and safety signs	.7135	11	High level
VAR8	Control of hazardous activities on site	.7458	10	High level
VAR9	Site meetings, especially for safety purposes	.7072	12	High level
VAR10	Ensuring health and safety education	.6687	13	Medium level
VAR11	Designated health and safety person	.8010	4	High level
VAR12	Communicating health and safety	.8645	2	Very high level
VAR13	Provision of first aid box	.8979	1	Very high level
VAR14	Workers' participation in hazard identification on sites	.5604	14	Low level
VAR15	Using outside health and safety consultants	.4937	15	Low level

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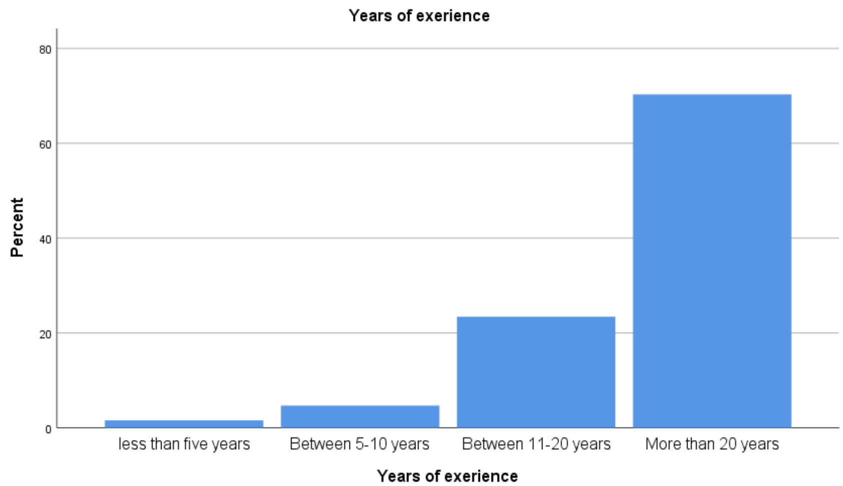

The graph demonstrates the percentage of participants in terms of years of experience. As shown, under 10% of participants have less than five years of experience, under 20% have 5-10 years of experience, under 40% have 11-20 years of experience, and more than 60% of the participants have more than 20 years of experience.

VI. Discussions

This research investigated the policies used to promote CSSM in the Jordanian context. For brevity, only the gist of the results is provided hereinafter.

As the pace of construction activities increases in fast-track projects, the probability of occupational injuries and fatalities increases (Jędrzejas and Sobala, 2018). Research result reveals two essential and critical policies to promote CSSM in fast-track construction projects in Jordan. Firstly, research respondents insisted on training construction workers to provide first aid in construction. A first-aid kit should be available and accessible. A first aid kit is a container used to hold goods and resources for an emergency. An occupational accident in fast-track construction projects is a sudden occurrence due to complex and hazardous activity resulting in serious injuries or death. It is a critical component that is frequently connected with ensuring the fast-track construction industry's safety. Research respondents believe that the greater the risk, the more trained individuals in first aid are required in the construction site. Getting first aid training and skills might be one of the most beneficial skills employees need to be acquainted with in fast-track construction projects. Construction workers ought to receive emergency response training to assist them to handle the worst-case scenario professionally and responding appropriately. The result of construction work-related injuries is determined by the severity of the injury and the quality of first-aid care provided (Fiske, 1999). The difference between life and death, fast vs slow recovery, and temporary versus permanent disabilities can be determined by how well-trained construction workers deal with injuries on construction sites.

Moreover, construction workers who have received first-aid training are eager to take personal responsibility for their safety and engage in safe conduct. Therefore, it may be more beneficial to provide first aid training to all employees at a business rather than just a few trained "first aiders." Therefore, the employer's responsibility is to offer first aid points and first aid supplies and train construction workers to provide first aid appropriately. Fairly standard practice is to have signs indicating the location of the first-aid kit and photographs of staff that provide first-aid treatment. In addition, it ought to be part of any induction course that the location of equipment and first-aiders is covered (Walsh, 1982.). Depending on the level of workplace occupational health and safety risk, the recommended ratio of "first aiders" to those not trained in first aid ranges from 1:25 to 1:50 (Vaaraanen et al., 1979).

Research participants' second most crucial safety policy is communicating health and safety measures. Improved communication tactics should promote safety awareness to minimize accident numbers and related costs. Contractors may benefit from increased safety communication by decreasing accidents, saving costs, and increasing productivity, thus enhancing added value. Communication is made efficient when mutual understanding is achieved at minimum resource expenditure (Schermerhorn *et al.,* 1994). For safety communication to be effective, it has to be understood, which is governed by the safety information to be communicated, the target audience, and the environment where information transmission occurs. There are two main communication media in fast-track construction projects: written and verbal, which can be used separately, depending on the message content (Preece *et al.*, 1998). Safety communications should be integrated with current quality and environmental systems to avoid duplication and contradiction of standards. An integrated system

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should boost staff morale; promote employee participation in safe behaviors, and lower incident rates.

Furthermore, communicating health and safety measures can strengthen the safety climate. Lingard (2019) defines safety climate as "perceptions that employees have about their work environment that function as a reference point for leading suitable and responsive task behaviors." Workers perceive signs in their workplace and form opinions about the behaviors emphasized and appreciated in their work context, enhancing safety behavior. Effective health and safety communication occurs vertically (between workers and managers) and horizontally (between workers). Effective and open communication about health and safety is essential in fast-track construction because it notifies workers about health & safety dangers, threats, and safe working practices. It also evokes vital information about workers' experiences and considerations and incites recommendations for ways to improve health and safety, enabling joint decision-making.

VII. Conclusion

This research argued that providing first aid training to construction workers is critical to promote health and safety in fast-track construction projects in Jordan and communicating health and safety measures. It also deduced that most consultants and contractors do not rely on outside health and safety consultants, and participation in hazard identification is infrequent because current safety hazard identification methods rely on expert judgment to identify risks. Thus, they cannot detect dangers in the diverse and dynamic nature of the construction environment continuously.

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Method of a Break-Even Analysis of Orbital Debris Mitigation and Remediation Costs

By Martin K. Zhu
The U.S. Federal Aviation Administration

Abstract- Through Monte Carlo simulations and a break-even analysis, this study monetizes the rising costs of orbital debris and space preservation. This study estimates the costs of allowing space debris to persist and proliferate using existing data and projections from the literature. This study assigns values to NASA's published space debris mitigation models to calculate the costs of space preservation. Estimating the costs of space debris has been hampered by a lack of information, owing primarily to commercial proprietary information. This study demonstrates how simple-realistic assumptions can transform sparse data into the foundation of a robust analysis. Furthermore, by conducting a break-even analysis of these costs based on defining quantitative variables in models, this study identifies the global cost savings and the likely timeline when the costs of space debris will equal the costs of space preservation. This study uses sensitivity analysis with alternative inputs to identify uncertainties in the costs of orbital debris and space preservation.

Keywords: externality, spill-over, space awareness, cost of orbital debris mitigation, cost of orbital debris remediation, proliferation, post-mission disposal, active debris removal, ADR, PMD, BEP, space economy, industry, 25 year rule, collision avoidance, sinking fund, pigouvian taxes, economics, statistics, uncertainty, forecast, simulation.

GJRE-J Classification: MSC: 85-XX

METHODOFABREAKEVENANALYSISOFORBITALDEBRISMITIGATIONANDREMEDIATIONCOSTS

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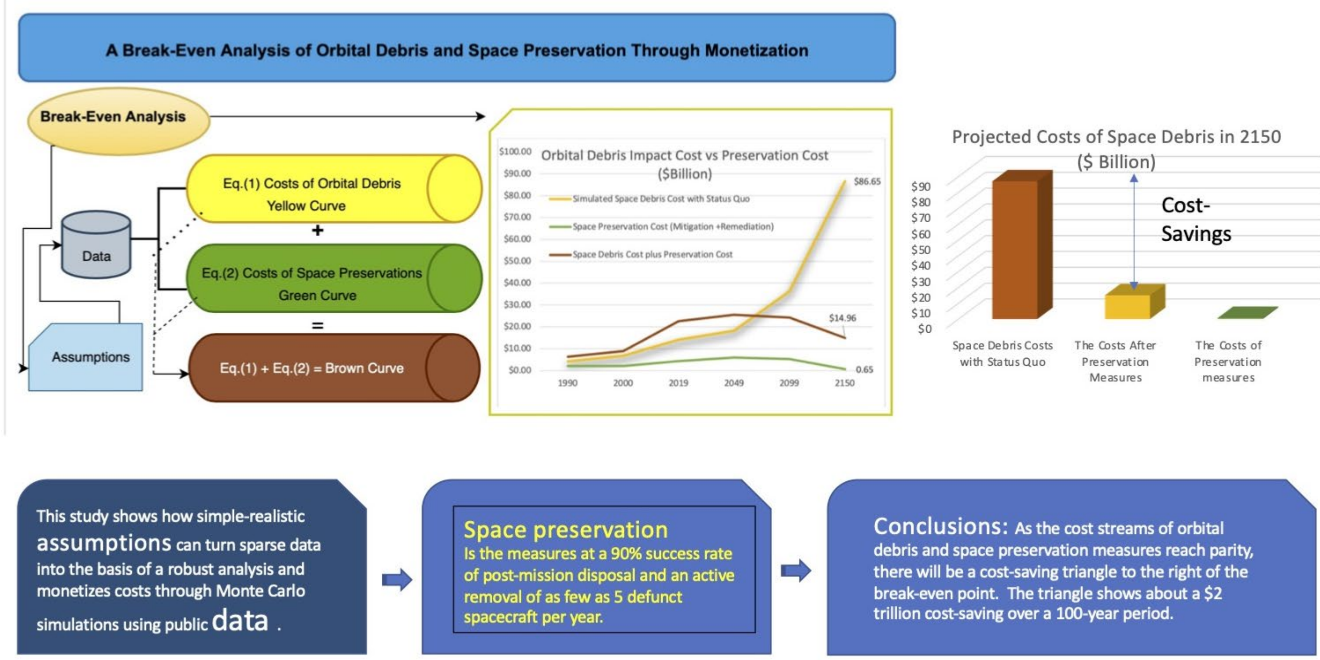

Figure 1: Graphic Summary

Key aspects of customization

- The break-even point (BEP) is the point at which expenditure equals revenue. The concept of BEP is used in this paper, where the cost stream of preserving orbital space meets the cost stream of extending orbital debris proliferation caused by orbital debris mitigation and remediation.
- The baseline for estimating space preservation is a 20%-30% rate of post-mission disposal (PMD), with no active debris removal (ADR). Concerning the target for sufficient and effective space preservation measures, this paper is linked to assumptions involving 90% success rate post-mission disposals and five active debris removals discussed in NASA studies (NASA ODPO ODQN 22-3, 4-7, cited by NASA IG-21-011.pdf) [1].
- Previously unavailable cost data is based on space experts' judgment, which is supported by observations from literature and media reports. Based on historical observations, it selects probability distributions and the highest and lowest possible values for simulation inputs.

Author: Ph.D, The U.S. Federal Aviation Administration.
e-mail: Martin.zhu@faa.gov

Specifications Table

Subject Area	Economics and Finance
More specific subject area	*Space safety and orbital debris*
Method name	*Break-even analysis, orbital debris monetization*
Name and reference of original method	*Space Economy* - BEA, Highfill et. al Dec. 2019 "Measuring the Value of the U.S. Space Economy" Viewed in Oct. 2021 at dx.doi.org/10.1787/9789264169166-en. - The OECD publication, 2020, "SPACE SUSTAINABILITY: THE ECONOMICS OF SPACE DEBRIS IN PERSPECTIVE" https://read.oecd.org/10.1787/a339de43-en?format=pdf (Viewed in May, 2022) - NodirAdilov, Peter J. Alexander & Brendan M. Cunningham, *An Economic Analysis of Earth Orbit Pollution*, 60 ENVTL. & RESOURCE ECON. 81 (2015) *Environmental & Resource Economics*, 2015, vol. 60, issue 1, 98 pages - The cost of space debris: The ESA, 07/05/2020, "The cost of space debris" https://www.esa.int/Safety_Security/Space_Debris/The_cost_of_space_debris (Viewed in May, 2022) - AIAA/ASCEND 2020 report, Space Economy Report-6.2020-4244.pdf - Dolgopolov et al., "Analysis of the Commercial Satellite Industry, Key Indicators and Global Trends" *Orbital Debris Environment* - NASA OIG Report 2021, IG-21-011.pdf pp7 and Figure 7, pp8. - The OECD publication, 2020, "SPACE SUSTAINABILITY: THE ECONOMICS OF SPACE DEBRIS IN PERSPECTIVE" - NASA ODQN, Oct 2018, 22-3. - NASA ODQN 24-1 February 2020, pp5 - NASA ODQN 25-4 Sep21, 2021. Study shows five confirmed accidental collisions between cataloged objects by 2021. - ESA Facts, 2020, viewed in Oct. 2021, https://www.esa.int/About_Us/Corporate_news/ESA_facts - ESA, "The Cost of Space Debris" July 5, 2020. It estimated the cost is around 5% to 10% of LEO and GEO operations. *Space Launch Activities* - Space Launch Report, "The World Successful Launch Total" from 2011-2021 Launch Logs, http://spacelaunchreport.com; - The FAA/AST U.S. Licensed Launches, https://www.faa.gov/ data_ research /commercial_space_data/ - Space Foundation September 2021, Space Economy for People, Planet and Prosperity. *Space Preservation Literature* - Bradley and Wein, 2009, Space Debris: Assessing Risk and Responsibility. - Dolgopolov et al. ASCEND 2020, "Analysis of the Commercial Satellite Industry, Key Indicators and Global Trends" - JC Liou · 2010 "An Updated Assessment of the Orbital Debris Environment in LEO", and ODQN, Vol. 14, Issue 1, January 2010, p 8. - J.-C. Liou, NASA ODQN Vol. 15-2, pp. 4-5 and Vol.15-3, pp. 7-8. Studies have indicated that removal of as few as five ADR per year can stabilize the long-term LEO environment. - M.K. Macauley 2015, The Economics of Space Debris: Estimating the Costs and Benefits of Debris Mitigation - Martin K. Zhu, JSSE Vol. 9, Issue 4, Dec. 2022, PP. 600-611. A Break-even Analysis of Orbital Debris and Space Preservation Through Monetization. https://www.sciencedirect.com/science/article/abs/pii/S2468896722001045 - NodirAdilov, Peter J. Alexander & Brendan M. Cunningham, *An Economic Analysis of Earth Orbit Pollution*, 60 ENVTL. & RESOURCE ECON. 81 (2015).

Resource availability	*Orbital debris related data* - ESA: https://www.esa.int/About_Us/Corporate_news/ESA_facts - NASA: NASA Orbital Debris Quarterly News (ODQN), Oct 2018, 22-3 https://orbitaldebris.jsc.nasa.gov/quarterly-news/ - NASA OIG Report 2021, IG-21-011.pdf - MIT, MIT International Center for Air Transportation *Space Activity Data* - Space Report, http://spacelaunchreport.com - Space Foundation, https://www.spacefoundation.org - The FAA/AST, for the U.S. commercial space launch data. https://www.faa.gov/data_research/commercial_space_data/ - AIAA/ASCEND, Space Economy Report

Introduction

Technically, orbital debris has been well defined in the space community. In addition, the community recognizes that orbital debris places safety and technical constraints on space operations. While researchers are studying how orbital debris affects the sustainability of commonly used Earth orbits, interest in an economic perspective on the problem is growing. Furthermore, the space engineering community is curious about the financial requirements for preserving space orbitals through debris mitigation and remediation.

The OECD published comprehensive economic research on the cost of space debris in 2020 [2]. Since 1979, the Orbital Debris Program Office (ODPO) of the United States Space Agency (NASA) has also conducted some well-known studies on the assessment of orbital debris impact and preservation measures for useful Earth orbits. This study employs a different methodology to monetize the costs of orbital debris than the 2023 NASA study (Colvin et al., 2023) [15].

This study estimates the costs of space preservation by using reliable data points and assigning values to NASA-published space debris mitigation models. Monetizing the rising costs of space debris and the costs of dealing with the problem provides policymakers and the space industry with a quantifiable metric for understanding the economic nature of orbital debris.

In space engineering terms, mitigation measure refers to actions of post-mission disposal (PMD) to prevent further orbital debris generation; remediation measure means actions of active debris removal (ADR) of defunct man-made objects generated in past space operations. Both measures preserve useful Earth orbits.

Method of Break-Even Analysis

The break-even point (BEP) is the point at which expenditure equals revenue. The break-even analysis method is frequently applied to an investment decision process, which can reveal whether and when the investment benefit will cover its cost given a price and quantity in its future timeline. This method is used in government regulatory analyses to determine when regulatory costs will be offset by public benefits from a finalized regulation. The concept of BEP is used in this paper, where the cost stream of preserving orbital space meets the cost stream of extending orbital debris proliferation. As a result, this break-even analysis method examines two cost streams, one of which is expected to reduce the other in the long run. In this case, the cost of space preservation can be viewed as an investment stream created to prevent the initial cost of orbital debris from spiraling upward. This method allows the study to emphasize the prospective costs of orbital debris, which are future costs that can be avoided or reduced if a corrective action is taken. This BEP analysis also identifies the global cost savings after the costs of space debris equal the costs of space preservation by conducting a break-even analysis of these cost streams. This kind of evaluation performs sensitivity analyses with alternative inputs to determine the effectiveness of mitigation and remediation options.

Data description

This paper's quantitative analysis incorporates observational, simulated, and derived data based on literature, experts' judgments, and publications by government agencies. Critical statistical inference uses data included in the studies published by the National Aeronautics and Space Administration Orbital Debris Program Office (NASA ODPO), debris collection risks, and the effective number of objects cited in NASA orbital debris quarterly newsletters (NASA ODQN), space economy data in Space Foundation reports, and space launch vehicle licensing data provided by the U.S. Federal Aviation Administration's Office of Commercial Space Transportation (FAA/AST) has made observational data available in the public domain, including the data used in NASA ODPO's orbital debris studies (NASA OIG, 2021) [1], J.-C. Liou (2011) [2], and other literature (N. Adilov et al. 2015) [3]. Unobservable data due to proprietary business practices are derived and simulated based on experts' judgment and data presented in literature. Employing variables for simulations, this study assigns statistical parameters to data points as they are probabilistic inputs. When constructing data sets pertaining to the cumulative number of catastrophic collisions for analyses and statistical inferences, this study applies collision scenarios in a low-case, a mid-case, and a high-case, as illustrated in (NASA's ODPO, 22-3, 2018, p. 5, Figure 5). The baseline for simulating the costs of orbital debris and the costs of mitigation in its studies matches findings and simulation results presented by NASA's ODPO, including the effective number of object projections, the 25-year rule implementation success rates (LEGEND simulations, Figure 4) [13], the cumulative number of catastrophic collision projections, the accidental explosion probabilities of large constellations, and catastrophic collision numbers. For spacecraft replacement simulation, table 3 aligns data with NASA ODPO's orbital debris studies for the data postulating collision probabilities of 0.01, 0.001, 0.0001, and 0 corresponding with active projects increasing by 1160%, 590%, 530%, and 5240%; PMD at 90%, 95%, 99%, and 99.9%; and a 100% success rate corresponding with catastrophic collision numbers of 582, 158, 40, 32, and 27 respectively (NASA's ODQN, 22-3, 2018, Figures 7 and 8, pp. 6 and 7)[5]. This study constructs unobservable data points for mitigation unit cost by using U.S. information at the current rate of post-mission disposal based on space experts' judgment. In the monetization procedures, all monetary values are expressed in 2019 dollars as undiscounted values, and then present values are derived at a 3% discount rate. Concerning simulation data, this paper uses Monte Carlo simulations with the statistics software application Palisade @Risks.

Method details

Models

The following models are designed for break-even analysis. The model determines a break-even point where the cost stream of orbital debris equals the cost stream of space preservation.

$$Equation(1):\ fa(n,p,t) = (A1 + R1) + (A2\ + R2) + (A3\ + R3) + \cdots + (At\ + Rt) + \varepsilon t,, where\ t = year, -- Eq.(1)$$

$$Equation(2):\ fb(n,p,t) = (M1\ + C1) + (M1\ + C1) + (M1\ + C1) + + (Mt\ + Ct) + \varepsilon t,, where\ t = year, -- Eq.(2)$$

Where Eq. (1) represents the cost of orbital debris and Eq. (2) represents the cost of space preservation. Both streams are functions of debris number *(n)*, collision probability *(p)*, and time *(t)*. Furthermore, in 1000 simulation runs, the mean of the variance residuals (ε_t) is assumed to be zero.

The starting time is 1990, and the ending time is 2150. All negative values are transformed into positive values.

Monte Carlo simulation is a process that assigns a probability distribution to each of the inputs. In Eq. (1), the inputs are the share of the space economy, the growth rate of the global space economy, and the cumulative number of spacecraft replacements, assuming the price of replacement is a constant. The inputs for Eq. (2) are the affected number of mitigation and mitigation cost per launch. Running simulations, a computer program calculates the output of the model a thousand times. Based on the defined input probability distributions, the computer program generates a different value for each input parameter on each trial. Statistics on the output variables of interest are calculated at the end of the simulation.

The term "space economy" is a novel concept in modern economics, with numerous interpretations. This paper employs the phrase "the space economy, which is the full range of activities and the use of resources that create and provide value and benefits to human beings while exploring, understanding, managing, and utilizing space. Hence, it includes all public and private actors involved in developing, providing, and using space-related products and services, ranging from research and development, the manufacture and use of space infrastructure (ground stations, launch vehicles, and satellites), to space-enabled applications (navigation equipment, satellite phones, meteorological services, etc.), and the scientific knowledge generated by such activities." (OECD 2012) [4].

I. The Monetization of the Costs of Space Debris

a) The model for estimating the cost of space debris

According to Eq. (1), the costs of space debris are comprised of two components: awareness costs (A_t) and mission replacement costs (R_t). In Eq. (1), the awareness cost (A_t) can be drilled down to be the global space revenue as an alpha (α) share of the global space economy (G_a) multiplied by a cost attribute rate (γ); mission replacement costs (R_t) can be expressed by an expected number of catastrophic collisions (N_a) multiplied by the replacement cost per spacecraft (P_a). As a result, costs of space debris Eq. (1) = awareness cost (A_t) + mission replacement cost (R_t) = $\alpha\gamma G_a(t)$ + $N_a P_a(t)$ + ε_t.

b) Variables

In the following, there are discussions of methods for estimating each of the parameters and variables related to Eq. (1).

(1) *Variable $G_a(t)$:* it stands for global space economy. This study simulates the global space economy from 1990 to 2150. This simulation contains a

historical time series from 1990 to 2019 and an extrapolation of the space economy from 2020 to 2150, a 160-year analysis period. This study goes through two stages. The first stage forecasts the global space economy from 2020 to 2049 based on the past 20 years of historical observations; the second stage simulates the space economy for the next 100 years by employing Monte Carlo 1000-runs.

The global space economy forecast is based on time series data between 2005 and 2019 from Space Foundation Reports [6]. The forecast model makes use of an exponential smoothing algorithm, which works best with Excel's forecast functions. The forecasted series output in Figure 2 is an example generated with target date, historical values, and timeline inputs. Table 1 displays the observations and the growth rates for the space economy

Figure 2 depicts the forecasting output for the period between 2005 and 2049. This paper compared this study to those conducted by other entities as corroboration. Table 1 shows that the average growth rate in the 10-year period from 2005 to 2020 was around 7%, except in 2015, when the space economy experienced negative growth. This $955 billion projection for the global space economy in Figure 2 is conservative when compared to bank projections for the year 2040 ranging from $926 billion to $3 trillion (Table 2).

The true outlook for a specific economic sector beyond 30 years, to a distant future in 2150, is probabilistic in a simulation process. With a conservative outlook, a long-term growth rate of around 7% for any economic sector of the global economy is deemed less likely. For this reason, this study undertakes Monte Carlo simulation approaches.

In the process of relating the space revenue to the global space economy, this study assigns probabilities to inputs with minimum, mean, and maximum values matching the output of the forecasted series in Figure 2; additionally, it assigns probabilities of 50%, 75%, and 90% to a 7% average growth rate to simulate the space economy time series.

(2) *Parameter alpha (α):* This study uses this parameter alpha (α) as a percentage rate to infer satellite and launch vehicle industry revenues or space industry revenues as a share of the global economy. This study discovers the parameter alpha (α) based on the scale of the U.S. space economy to calculate global space revenue using historical data. As of 2019 (Space Foundation Report 2020), the satellite industry's revenue accounts for 74% of the space economy [6]. Using that observation as a data point, this study derives the space industry revenue by multiplying the space economy time series $G_a(t)$ by the parameter alpha (α), which equals 74%.

(3) *Cost attribution rate (γ):* This rate means a percentage of space revenue is attributable to orbital debris awareness costs. This paper quantifies the cost attribution rate (γ) in the range of 1% to 5% based on the corroboration of various historical data points, experts' opinions, and the literature (ESA, "The Cost of Space Debris," July 5, 2020) [10].

(4) *Variable $N_a(t)$:* This represents the expected number of catastrophic collisions. The simulation of cumulative catastrophic collision numbers is a probabilistic process. This analysis uses cumulative collision numbers between 30 and 270 around the year 2150, aligning with the projections reported by NASA ODPO (Figures 3 and 4). There are two sources of explosions: background orbital debris explosions (BG_exp) and large constellation orbital debris explosions (LC_exp). This range matches the assumptions, defined as a range between the upper bound at which GB_exp with post-mission disposal at a 90 percent rate (BG_exp_90% PMD) and LC_exp_90% PMD, and the lower bound of BG_exp_90% PMD and LC_exp_99% PMD for 50 years of replenishment and 6,700 spacecraft (ODQN 22-3) (Figure 5) [6].

(5) *Variable $P_a(t)$:* It is the value of each replacement, which is set between $50 million and $96 million for 500 Monte Carlo runs to construct a time series of mission replacement costs (R_t). The initial value is $96 million, which is decreasing over time.

c) Estimate the costs of space debris

In a nutshell, the following steps are taken in this paper to monetize the costs of space debris.

(a) Simulate the global space economy time series $G_a(t)$ by setting statistical weights at 50%, 75%, and 90% for the space economy based on the average 7% growth rate of the past 15 years.
(b) Derive the space revenue time series by multiplying $G_a(t)$ by the parameter alpha (α) at a 74% rate.
(c) Simulate the debris awareness costs of three scenarios by applying the cost attribute rate (γ) ranging from 1% to 5% to the space revenue.
(d) Simulate the space mission replacement cost in three scenarios. Multiplying lower-case (50%), mid-case (75%), and higher-case (100%) for cumulative catastrophic collision numbers by a unit replacement value of $96 million to simulate the values of mission-spacecraft losses.
(e) Calculate the present value of the costs of space debris at a 3% discount rate and substitute simulation output into equation (1).

d) Assumptions and Data

The models rest on the assumptions used in NASA's ODPO study for collision probabilities, area-to-mass ratio, and active object predictions [5]. The cost of

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orbital debris will continue to rise as orbital debris is allowed to proliferate. The projection of long-run space economy growth and space revenue are primary inputs into the analyses used to support long-term predictions of orbital debris costs. Uncertainties are inherent in the predictions from numerical simulation models for space economy and the cost attribution rate. It is appropriate that uncertainties are factored into the cost simulations by setting a range of probabilities to a current observed average growth rate and the experts selected cost contribution rate ($\alpha = 5\%$). Since the 2020 ESA research paper predicts the cost contribution rate (α) to be 5%, this paper goes above and beyond to confirm the rate with observations from the space community [10]. These observations are discussed in the original paper [14]. Being cautious and not overstating the long-term cost of orbital debris, the paper applies a range of the cost contribution rate (α) range of 1% to 5% to the forecasted space revenue.

II. The Monetization of Space Preservation

The costs of post-mission disposal (PMD) and active debris removal determine the monetarization of space preservation measures (ADR). PMD options include uncontrolled atmospheric disposal, controlled disposal, direct retrieval, heliocentric Earth-escape disposal, and maneuvering post-mission objects to disposal orbits. ADR, or direct retrieval disposal, is a method of orbital debris disposal that involves removing human-made objects from protected Earth orbits beyond the mitigation guidelines currently adopted by the international space community.

a) The model of estimating the costs of space preservation

Eq. (2) shows that the costs of space preservation include mitigation costs (M_t) and remediation costs (C_t). This equation can be further deconstructed by multiplying the PMD success rate (β) by the mitigation unit cost (C_b) and the affected launch numbers prediction (N_b) to get the mitigation cost (M_t), plus the expected number of active removals of defunct spacecraft (N_c) multiplied by the present value per launch (P_c) to get the remediation cost (C_t), plus the mean of the variance residuals (ε_t). As a result, costs of space preservation Eq. (2) = mitigation costs (M_t) + remediation costs (C_1) = $\beta C_b N_b$ (t) + $N_c P_c$(t) + ε_t.

b) Variables

In the following, there are discussions of methods for estimating parameters and variables related to Eq. (2).

(1) *Parameter beta (β):* It is a success rate in the form of a percentage for conducting global post-mission disposal (PMD). The baseline for the estimation of space preservation in this analysis conforms to a 20% to 30% rate of PMD with no ADR occurring. As a result, the initial value of parameter (β) is set for an initial success rate of 20% for PMD, which is assumed to increase linearly over time to a rate of 90% in 2049.

(2) *Variable $C_b(t)$:* It is a mitigation unit cost that is attributable to additional propellant, debris avoidance R&D, software and hardware testing, and engineers' time. Because global mitigation cost data are not available, this analysis extrapolates global mitigation costs from U.S. data, which are based on experts' judgment and knowledge. This study establishes experts' opinions on mitigation unit cost for Monte Carlo simulation runs ranging from a minimum to a maximum value. The simulation runs yield a mean of experts' judgments of about 4% of a single medium-sized vehicle's launch cost.

(3) *Variable $N_b(t)$:* This is the global affected number of launch vehicles subject to PMD at a 90% success rate. This paper presumes that future mitigation costs will be primarily attributed to commercial spacecraft launch activities. As a result, this study uses numbers of commercial launches excluding the suborbital as a reliable predictor of affected launches subject to mitigation. Furthermore, because the affected launch number is a subset of global total launches, this study estimates a multiplier parameter (X) based on U.S. data to infer the global mitigation N_b(t). Table 4 data shows that the global space launch total is 4.21 times the U.S.-licensed space launches based on historical world launch data between 2011 and 2020 (Bureau of Transportation Statistics, bts.gov) and U.S. commercial spacecraft launch license data (FAA/AST) [10]. To corroborate the finding, Figure 3 depicts the derivation of the multiplier parameter (X) using the statistics software tool (Palisade @Risks) to infer the multiplier (X) parameter to be 4.28, which scales the U.S. effective number of space objects to the global total over a ten-year period. Using Monte Carlo simulation, the distribution shape appears close to a normal distribution in the range of a minimum of 2.9 to a maximum of 6.21, and around the mean of 4.28 (the multiplier parameter X) from Monte Carlo 500 runs at a 90% confidence level within 3.3 and 5.4. The statistics comparison table adjacent to the distribution figure uses two colors, red and blue, for the purpose of comparison between Monte Carlo simulation and PERT distribution. In Figure 3, the red area represents the inference value area covered by a 90% confidence level using Monte Carlo simulation, while the blue area covered by the PERT distribution with the minimum (2.85) and maximum (4.15) values shown.

(4) *Variable* N_c*:* This is the expected number of active removals of defunct spacecraft from LEO and GEO. It is assumed to be zero in 2020 and five per year by 2049.

(5) *Variable* P_c*:* This is the present value of the single launch cost for the remediation. This paper assumes an undiscounted value of the LEO launch cost of approximately $96 million for each ADR mission. Over time, its present value per launch decreases.

c) Estimate the costs of space preservation

In sum, estimating the costs of space preservation involves the following steps.

(a) Estimate U.S. unit costs of PMD mitigation by averaging the costs of PMD options such as atmospheric disposal and maneuvering upper stages into storage orbit. The costs of each mitigation option are determined by the subject experts.

(b) Estimate Eq. (2) the multiplier parameter (X) by scaling the U.S. effective number of space objects to the global total over a 10-year period (the NASA ODQN between 2011 and 2020).

(c) Derive the world mitigation costs by multiplying the U.S. mitigation cost by the multiplier parameter (X), which is a parameter that scales US mitigation cost estimates to the global total.

(d) Simulate the costs of future active debris removal. The global remediation costs are gradually phased in and are expected to reach the maximum ADR per year in 2049. Presumably, five active debris removals (ADR) will cost approximately $96 million. The costs of remediation are fully accounted for when 5 ADR is in practice. The cost per ADR decreases over time.

(e) Estimate the present value of the costs of space preservation using a 3% discount rate and plug simulation results into the equation (2).

d) Assumptions and Data

The models are based on the assumptions made in NASA ODPO's study [5]. In the study, its simulation graphics (Figure 6) illustrate conducting PMD at a 90% rate and removing at least 5 defunct spacecraft per year to effectively stem the rising trend of the effective number of objects or the trend of orbital debris. The goal is reached when the preservation measures are fully implemented. The estimation of the preservation cost can be varied by the cost of forecasted PMD, the cost per ADR, and the number of ADR in a time series. The cost of forecasted PMD measures incorporates uncertainty in the predictions from the model for space launch forecasting and space vehicle launch cost. The data used for global space vehicle launch forecasting are based on US launch forecasting data. While a reliable global mitigation cost is not available, the rationale for using the U.S. launch forecasting data is that the U.S. data has the most available data points, and the U.S. currently accounts for the lion's share of the global space launches. Technically, using the X multiplier, which is a parameter that scales the U.S. mitigation cost estimates to the global total, is appropriate to bridge the data gap.

III. Break-Even Analysis

Using Eq. (1) and Monte Carlo simulations, the best-fit model is an exponentially upward trend depicting the cost of orbital debris. As shown in Figure 7, the yellow curve (I) represents the cost of orbital debris, which stands for the cost stream of orbital debris proliferation. Under the status quo, post-mission upper stages are minimally mitigated at a 25% (the midpoint of 20%–30%) rate of PMD. Applying Eq. (2), the green curve II represents the cost of preservation, including mitigation and remediation.

The yellow curve (I) is viewed as an exponential trendline, illustrating a rise in value at an increasing rate. The green curve (II), representing the cost of space preservation, is shown as a logarithmic trendline, which quickly increases then levels off. Although both trendlines are rising, they are converging and then crossing at their parity values at a break-even point.

The third curve (brown, curve III) embodies the cost of orbital debris and the cost of space preservation. The presumption is that the impacts of orbital debris will be stabilized when the active removal of five defunct spacecraft per year and PMD with a 90% success rate are fully phased in at some point on the time horizon. When the total amount of orbital debris is stabilized, its cost will be leveled because its accumulation rate is approaching a minimum. As a result, the third curve can also be viewed as the realization of the cost of orbital debris retention plus the costs of recurring preservation.

The third curve is the sum of the values represented by curves I and II before the break-even point (BEP). Following the BEP, curve III is the sum of sunk or unsalvageable costs embodied in future spacecraft operations caused by orbital debris plus the cost of space preservation. Figure 7 depicts how debris mediation and remediation measures can slow or even halt the growth of orbital debris costs. As a result, when sufficient preservation measures are fully implemented, presumably in 2049 according to the NASA OIG's report 2021 [1], the cost of debris awareness and replacement will have passed its peak and will begin to fall. As a result, at the BEP, the brown curve (III) intersects the yellow curve (I). When the BEP is passed to the right, the variable cost includes the incremental cost of the mitigation and remediation over and above the sunk cost. Overall debris costs are decreasing from the BEP due to avoiding a future rise in the cost of space objects. Both the brown curve (III) and the green curve

(II) are decreasing in part due to an economic discount mechanism that uses a 3% discounted rate to calculate discounted future value.

Figure 7 shows that the cost of space debris (the yellow curve) passing BEP from the left is greater than the brown curve (III); the difference between the two cost curves represents the cost savings. The brown curve (III) represents the reduced cost of orbital debris and space preservation. It means that the cost of orbital debris would be at an elevated level, as shown by the yellow curve (I), without further measures of space preservation. The accumulative cost savings over the next 100 years will equal the triangle area closest to the BEP, below the yellow curve (I), and above the brown curve (III). The cost savings will be enormous—approximately $2 trillion.

IV. Sensitivity Analysis

Policy factors used in this sensitive analysis are considered, as shown by Figure 8. They are the discount rate for present value, the number of active accumulations of objects, the mass of active objects, the time factor for phasing in the preservation measures, and sustained objects in protected orbits. This paper demonstrates that the BEP movement resulted from changes in these independent variables.

The total amount of orbital debris is equal to the number of active objects (n) multiplied by the total object mass (m) multiplied by the object-year in orbit (t). The third cost curve (III), which is dependent on the three variables multiplied by the cost per unit (i.e., n * m * t * $), influences the expected outcomes of BEP. When variables change, this model explains BEP movement.

The number of active space objects is assumed to be the same as the number of space vehicles launched. The upper stages of post-mission spacecraft contribute the most mass to orbital debris. When this variable is applied to the US share of total commercial launches being surpassed by shares from other countries such as China, India, Korea, Brazil, Saudi Arabia, and so on, the model predicts that debris mitigation costs will rise, pushing BEP to the right.

The time factor refers to the phases of implementation of the anticipated preservation measures. The preservation measures are the PMD at a 90% discount rate and the 5-ADR, both of which affect BEP results. According to this model, delaying active debris removal in practice would result in a significant reduction in cost savings because delayed remediation would put the break-even point (BEP) at a higher cost level, thus pushing the BEP further into the future. As measured by the above model (n * m * t), a higher BEP level is the consequence of rising cumulative debris. Another scenario in which the timing factor pushes BEP to the right assumes that the scheduled 5-ADR rate falls to 2 ADR per year. Because the spacefaring community in this scenario would have to spend more on awareness costs, both mitigation and remediation costs would rise in the future. As a result, insufficient ADR measures in timing contribute to raising the cost level predicted by the breakeven point (BEP).

The cost of space debris is affected by the projected effective number of space objects associated with future launch activities as well as the timeline for implementing effective preservation measures. BEP movements and changes in the cost of realized orbital debris are explained by sensitivity analyses. A sensitivity analysis was conducted by considering the increase in active debris removal (ADR) to be greater than five used space stages. A number higher than 5 ADR would add additional remediation costs for space preservation. But that might be necessary to counter either used space stages rising faster than what observations suggest or remediation compliance being delayed to a distant future. However, declining ADR costs over time could offset the costs incurred with higher ADR numbers. Additional measures can be paid for by contracting for future remediation costs and expanding the long-term cost savings. All of that is reflected by the triangle area on the right side of the BEP.

When the discount rate for assessing present value goes up, it makes today's dollar more valuable than a present value discounted by a lower discount rate, which should be around the nominal long-term growth rate of the space industry. As this study has a long analytical period of over 100 years, a discount rate greater than 3% will overly discount future value. The present values of the costs in this break-even analysis use a 3% discount rate. The federal Office of Management and Budget (OMB) directs all U.S. federal agencies to use 3% for long-term analysis in federal regulatory analyses. Therefore, using a 3% discount rate greater than a long-run growth rate to calculate the present value of the cost is appropriate.

V. Conclusion

The break-even analysis is an important decision-making tool that informs policymakers about space preservation choices and timing urgency. This analysis has made many simplifications because historical data are difficult to get. This paper strictly relies on NASA's studies regarding the accumulative number of space objects, orbital debris mass, collision probability, and space preservation measures. Since some of these assumptions are implicit, this paper takes an approximation of these observations without looking at detailed study data. As the cost of orbital debris is based on space activity forecasting, using U.S. observations can be problematic as the global space competition changes the reality quickly. The timing assumptions are critical for constructing the figures of

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the break-even analysis. In the end, this analysis extends the time frame into the distant future and thus limits its applicability. Using multi-decade timescales, a wide range of probabilities for the future's monetary value should be considered.

Appendix

Table 1: Global Space Economy between 2005 and 2020 (Space Foundation Reports) [6]

Year	Global Space Economy* ($B)	Historical Growth Rate %
2005	175	
2006	195.3	12%
2007	215.6	10%
2008	235.9	9%
2009	256.2	9%
2010	276.5	8%
2011	289.8	5%
2012	304.3	5%
2013	314.2	3%
2014	330	5%
2015	323	-2%
2016	329	2%
2017	385	17%
2018	414.5	8%
2019	423.8	2%
2020	447	5%

Table 2: 2040 Projections of the Size and Composition of the Space Economy

Space Economy Projections ($B)	2016	2040	Compound Annual Rate of Growth
UBS	$340	$926	4.3%
Morgan Stanley	$339	$1100	4.9%
U.S. Chamber of Commerce	$383.5	$1500	6.0%
Bank of America	$339	$2700	9.0%
Goldman Sachs	$340	$3000	9.5%
Average compound Annual Rate of Growth			6.7%

Published by: Institute for Defense Analyses (2020), cited by JSTOR[11]

Table 3: Collision probabilities and catastrophic collision numbers used by NASA's ODPO

Projected for Year 2215			
Collision Probability over 5-years mission	Active Projects Increase by %	PMD %	Catastrophic Collisions Number
0.01	1160%	90.0%	582
0.001	590%	95.0%	158
0.0001	530%	99.0%	40
0	524%	99.9%	32
No Constellation	0	100%	27

Source: NASA, ODQN 2018 22-3, Figure 7 and 8.

Table 4: Successful space vehicle launch scale of the US vs. the world

Successful Space Launch	The World Total	The US Total	The World Multiplier
2011	78	17	4.59
2012	73	12	6.03
2013	78	20	3.90
2014	88	20	4.40
2015	81	14	5.79
2016	82	17	4.82
2017	84	22	3.82
2018	111	35	3.17
2019	97	32	3.03
2020	110	39	2.89
Mean			4.21

Source: Bureau of Transportation Statistics (bts.gov) –The world successful launches; The US Licensed number, the FAA/AST https://www.faa.gov/data_research/commercial_space_data/.

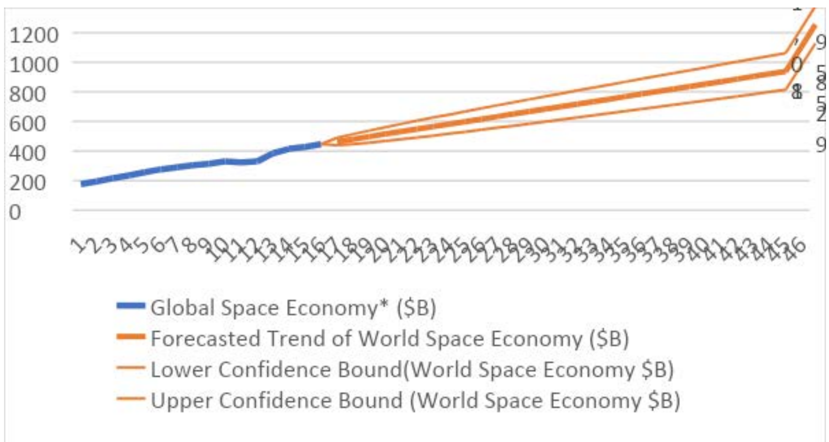


Figure 2: Forecasting of the global space economy

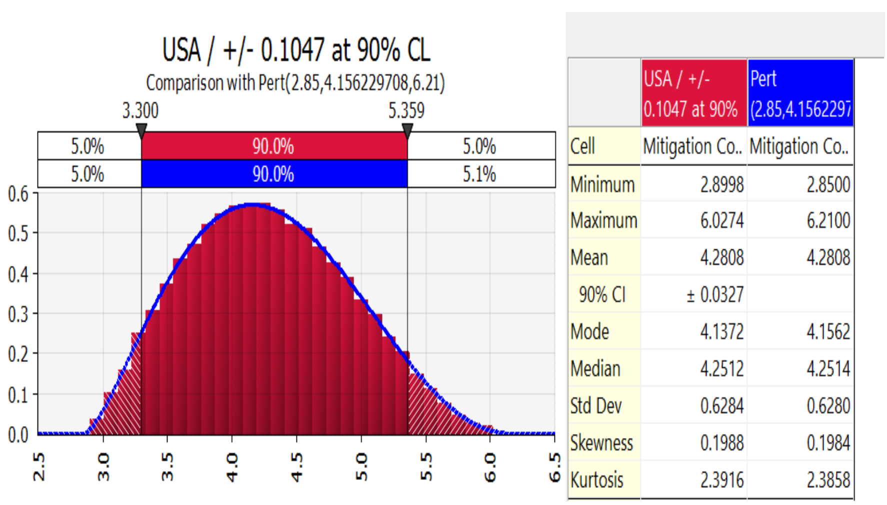
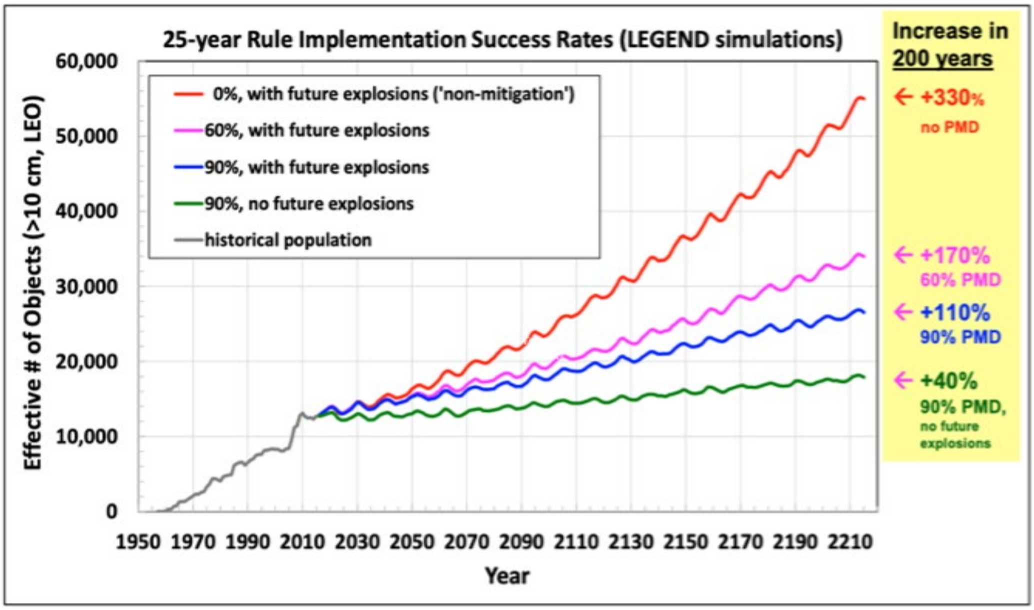
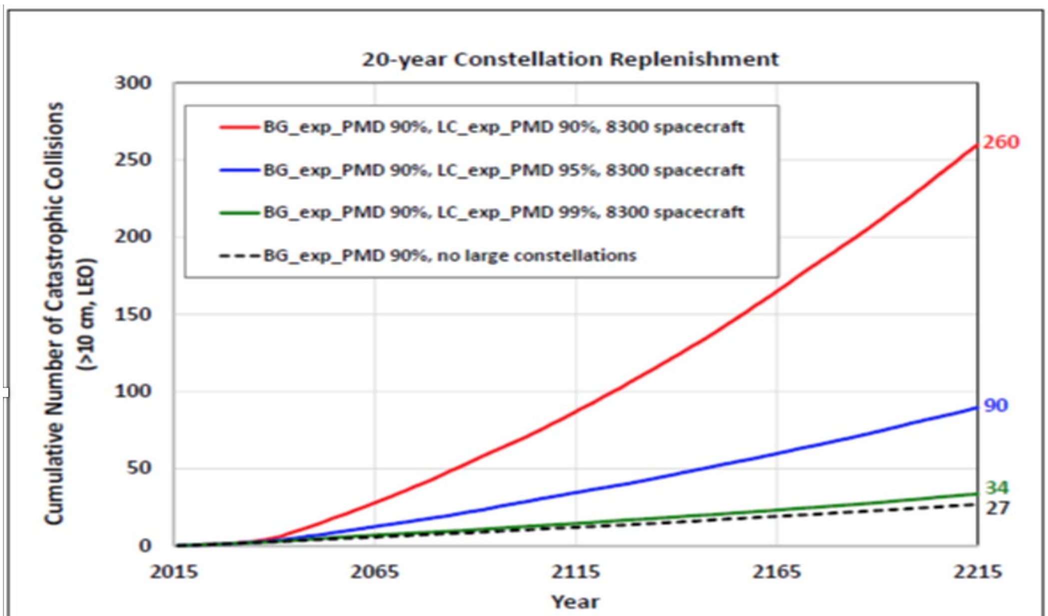


Figure 3: Relationship between the size of the US space sector and the size of the remaining global Space sector



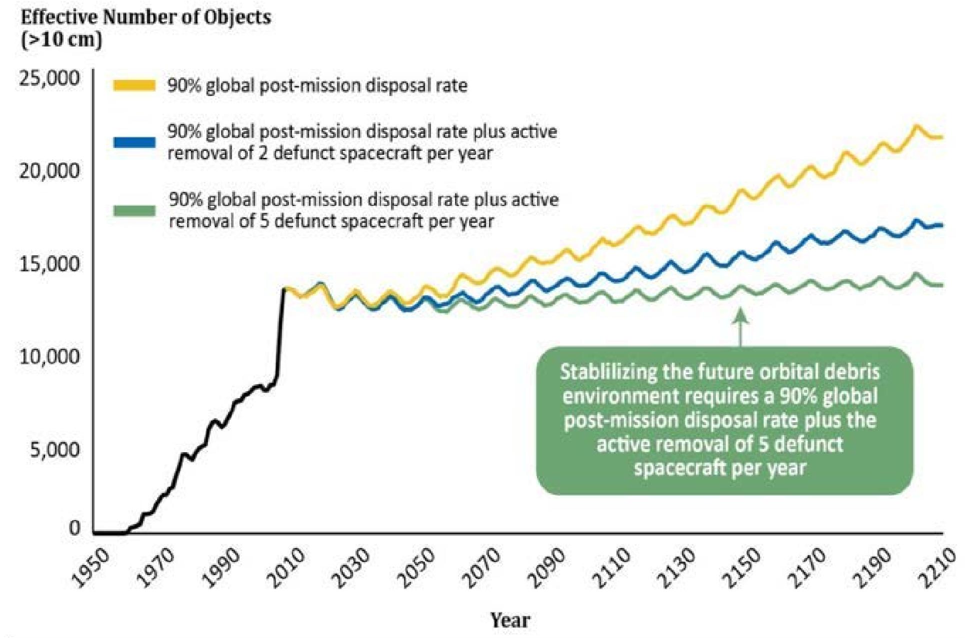
(Source: NASA's ODPO, Orbital Debris Quarterly News 24-1 February 2020, p5) [5]

Figure 4: Projections based on the 25-year rule compliance levels and accidental explosions. Projection results are based on averages of 100 Monte Carlo simulations each.



Source: NASA ODPO, Orbital Debris Quarterly News 22-3 September 2018, p5

Figure 5: Cumulative collision numbers between 30 and 150 in 2150.



Source: NASA OIG depiction of ODPO information

Figure 6: Global PMD at a 90% rate plus ADR of 5 defunct spacecraft per year is needed to stabilize LEO's Orbital Debris Environment [1]

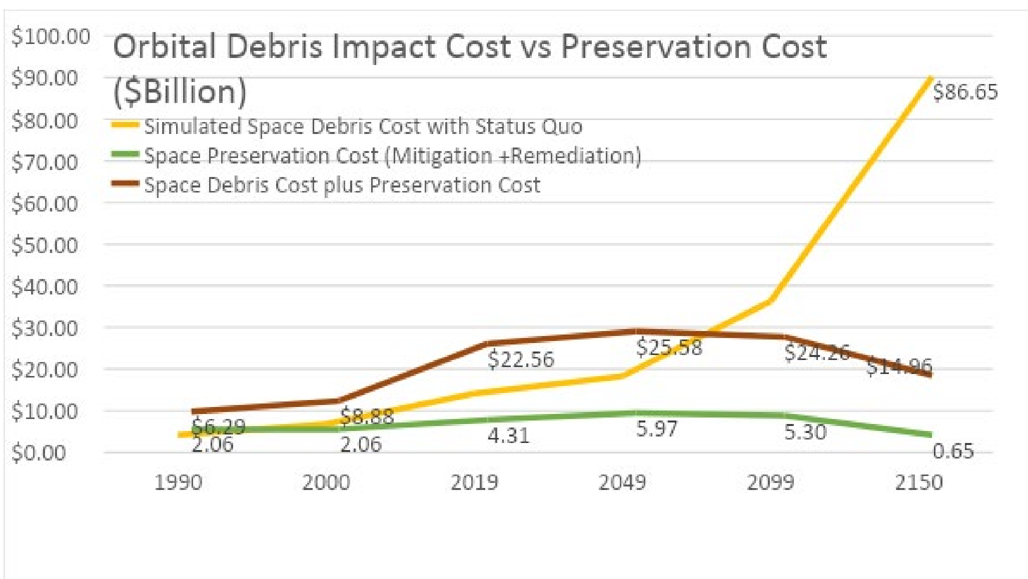


Figure 7: The cost stream of extending orbital debris proliferation (curve I) crosses the cost stream of space preservation (curve III). The point of intersection is the break-even point (BEP).

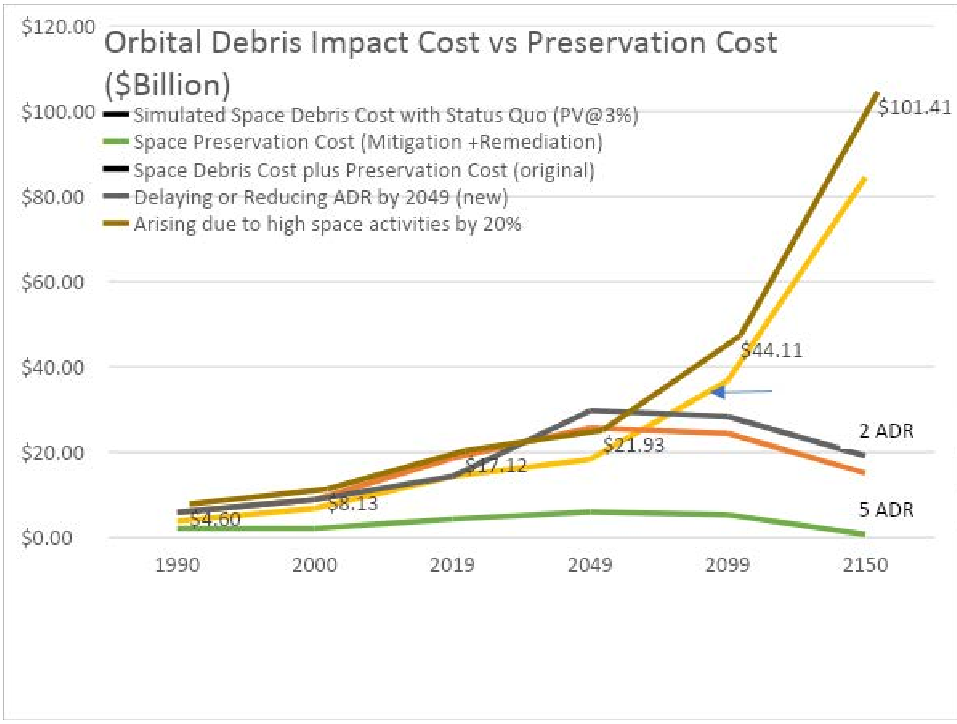


Figure 8: An example of sensitivity analysis.

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Declaration of interests

- The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Modelling Personnel Safety on Floating Production, Storage and Offloading (FPSO) Systems

By Kingsley E. Abhulimen

Abstract- This paper presents a model to plan personnel safety on FPSO platform systems. A Transshipment System model of utilities, personnel worker safety status on FPSO Platform is derived from Bow Tie Risk system and pinch technique. Data obtained from deepwater multinational oil and gas operator in Nigeria is used to simulate the safety index of personnel safety from 10% to 90% on the risk threat targeted. The plots of risk reduction and safety composite graph for the risk target are presented for personnel on critical and non-critical assignments and safety targets for the process worker on FPSO simulated in MATLAB software environment to be γ_{T1} (0.553733), γ_{T2} (0.49836), γ_{T3} (0.276867), γ_{T1} (0.110747), and γ_{T2} (0.055373), for safety targets of 100%, 90%, 50%, 20%, and 10% consecutively.

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MODELLINGPERSONNELSAFETYONFLOATINGPRODUCTIONSTORAGEANDOFFLOADING FPSOSYSTEMS

Strictly as per the compliance and regulations of:

Modelling Personnel Safety on Floating Production, Storage and Offloading (FPSO) Systems

Kingsley E. Abhulimen

Abstract- This paper presents a model to plan personnel safety on FPSO platform systems. A Transshipment System model of utilities, personnel worker safety status on FPSO Platform is derived from Bow Tie Risk system and pinch technique. Data obtained from deepwater multinational oil and gas operator in Nigeria is used to simulate the safety index of personnel safety from 10% to 90% on the risk threat targeted. The plots of risk reduction and safety composite graph for the risk target are presented for personnel on critical and non-critical assignments and safety targets for the process worker on FPSO simulated in MATLAB software environment to be γ_{T1} (0.553733), γ_{T2} (0.49836), γ_{T3} (0.276867), γ_{T1} (0.110747), and γ_{T2} (0.055373), for safety targets of 100%, 90%, 50%, 20%, and 10% consecutively.

I. Introduction

Modern day research work on personnel risk analysis focus on safety of complex production systems to determine equipment, instruments and hazards critical to risk and reliability design (Caoeatal (2010), Suardin et.al (2009), Liuetal, 2004, Abhulimen, 2009, Abhulimen and Susu, 2002). Several risk techniques such as fault tree analysis, bow tie, failure mode effect and critical analysis (FMECA), Layers of protection and safety assessment management techniques are available in technical literature (Yang, JB and Singh, M.G (1994), Khan, F.L and Abassi S.A, 1991, Khan, F.L and Abassi S.A, 1998). Nevertheless, none of these methods address prioritizing equipment and process systems critical to optimizing personnel safety (Caoeatal (2010), Suardin et.al (2009), Liuetal, 2004). The personnel safety analysis framework implemented within any risk model are based on the following criteria 1) Selection of a safety strategy on hazard of different component of the system. 2) Appropriating basis for accessing information on redundant systems not critical to the safety of the process or facility. 3) Allotting measures for the correlation of complexity of risk and safety pair of complimentary hazards and reliability systems to prevent loss in containment. 4) Evaluating performance and effectiveness of safety systems. This paper explores the use of pinch technique to achieve effective planning of personnel safety to minimize threat and optimized crises management on an FPSO operated by a Nigerian Deep water oil and gas operator.

Author: e-mail: syntechsysglobal@gmail.com

II. Risk Assessment Method using Weight Index

Abhulimen presented a model for analysing safety of series and parallel risk systems which incorporates the weighted safety factors represented below

For series systems, risk potential is defined

$$Risk\ \ Potential = \frac{\prod_{i=1}^{n} r_i^{\omega_I}}{1-\prod_{i=1}^{n}(1-R_{si})^{\omega_I}} \tag{1}$$

For Parallel Based Risk Systems

$$Risk\ \ Potential = \frac{\prod_{i=1}^{n} r_i^{\omega_I}}{1-\prod_{i=1}^{n}(1-R_{si})^{\omega_I}} \tag{2}$$

r_i is the risk variable and R_{si} are the reliability of systems, and ω_I are the associated weights to the risk, where risk is defined by eqn. 3

$$\mathbf{r_i(t) = 1 - e^{-\lambda_\omega t}} \tag{3}$$

The reliability is obtained by making a subtraction of the risk from 1 to give reliability of of the risk component presented in eqn 4.

$$R_{si} = 1 - r_i(t) \tag{4}$$

For parallel risk systems we present hazard function as the algebraic sum presented as eqn.5

$$\lambda_{\omega P} = \sum_{i=1}^{N} \omega_i \lambda_i \tag{5}$$

For series risk systems we present the hazard function as the product sum of hazard rates of the indvdual components:

$$\lambda_{\omega S} = \prod_{I=1}^{N} \lambda^{\omega_i} \tag{6}$$

The weight index is given by equation 7:

$$\omega_i(t) = (1 - SRF_i)\left(\frac{t}{\eta_i}\right)^{\beta_i - 1} \quad (7)$$

SFR_i is a safety factor to different hazard systems, t is the time, η_i is the maximum time for the system to have 66.7% of failure from the weibull classification, β_i and is the hazard shape function.

a) *Safety Targeting by Pinch Technique:* A new technique based on pinch analysis is presented to model management of safety of personnel resources on complex Floating production and process systems. The method is stated below:

1. Assign three event domains in risk analysis in a typical Bowtie:

Event domain 1: Primary hazards system's generating threat streams:

Event Domain 2: Secondary threat streams from the hazard events Domain:

Event Domain 3: Safety controls strategy to contain threats from releasing containments for credible accident scenarios.

2. Define a transshipment model as in a hierarchy. See Figure 1
3. Deploy pinch method to resolve personnel safety without compromising the risk and threat domain matrix
4. The pinch point is located at the point when net risk transfer is zero based on the cascaded design.
5. Figure 1 is a Bow Tie Transshipment model. $\Delta\lambda_n$ is a risk-threat stream and $\lambda_{j+1h} = \lambda_{jh} - \Delta\lambda_h$ is the risk-non threat streams between $h = 1.,2........n$ and added to the risk –non threat stream $\lambda_{j+1c} = \lambda_{jc} + \Delta\lambda_h$ $h = 1.,2........n$ and $c = 1.,2........m$. The safety utilities are used to protect that is: $r_i(t) = 1 - e^{-\lambda_\omega t} = 0$
6. Therefore, threat in step 5 is transfer across boundaries to reduce its risk-threat load such that $\lambda_{j+1h} = \lambda_{jh} - \Delta\lambda_h$, and safety utilities are added as $\omega_{j+1h} = \omega_{jh} + \Delta\omega_h$ and vice-versa as $\omega_{j+1c} = \omega_{jc} - \Delta\omega_c$

Step 1 to Step 6 establishes a transshipment model design to achieve risk reductions in complex production risk process which can be determined in two domains- Level 1 and Level 2 below:

i. *Level 1*

The systems and subsystems in a Bow-Tie are arranged in order of the risk hierarchy with riskier systems located at the top of the transshipment superstructure and less risky systems place at the bottom of the transshipment superstructure and labeled in that order $h = 1.,2........n = r$ representing the risk-threat utilities and $c = r+1, r+2,........m$ representing the risk-non threat streams with the pinch point located r.

ii. *Level 2*

A) The e-Learning tableau tracks plant, process hazard or accident history, risk structure in variables, age, and asset integrity in a defining linear programming tableau.
B) The e-Learning database program receives series of instructions to optimize archiving of hazard data and lessons learnt from previous threat events.
C) The e-Learning model analyzes data output by a key factor K_h within a database e-Learning module using a neural network training program.

b) *Safety Targeting-Pinch Criteria*

Pinch methods assume the following:

1. There are no non threat (safety) utilities/systems above the pinch point
2. There are no net risk at the pinch point, the net risk is zero
3. There are threat (threat) utilities/systems below the pinch point.
4. Transshipment Model of the Bow Tie System

   H- Threat Stream (Riskiest)

   C- Non threat Stream (Safest)

   N –Risk Components- Unprotected 1- Safest System well protected

On a Scale of 10

Hazard		Linguistic Logic	Numerical Constants
$F_{FR}(0)$	-1	Very Low (Negligible)	(VL)
$F_{FR}(1)$	0	Low	(Lo)
$F_{FR}(2)$	1	Reasonably Low	(RLo)
$F_{FR}(3)$	3	Average	(A)
$F_{FR}(4)$	5	Reasonably Frequent	(RF)
$F_{FR}(5)$	7	Highly Frequent	(HF)
$F_{FR}(6)$	9	Too Frequent	(TF)
$F_{FR}(7)$	-11	Worst Case	(WC)

CS is the numerical ranking of severity of failure effects. The linguistic terms are: negligible (N), marginal (Ma), moderate (Mo), critical (Cr) and catastrophic (Ca). The linguistic terms describing consequence can be assigned the following Fuzzy Numeric Constant:

Hazard Class	Linguistic	Numeric	
Zero-Fatality	(Negligible)	F_{CS} (1)	0
Minor	(Marginal)	F_{CS} (2)	0-1
Major	(Moderate)	F_{CS} (3)	2-10
Severe	(Critical)	F_{CS} (4)	11-50
Fatality	(Minor Catastrophic)	F_{CS} (5)	51-100
Disaster	(Catastrophic)	F_{CS} (6)	100+

FCP is the probability consequences with linguistic qualifications as remote to occur, very unlikely (U), unlikely (RU), likely (L), very likely (HL) and definite (D). Have Hazard Class F [1, 2, 3, 4, 5] defined has numerical value assigned as:

Hazard Class	Hazard Rate	Fuzzy Class
Definite to	[>10]/yr	F_{CP} (0)
Very likely	[>1-10] /yr	F_{CP} (1)
Likely	[0.01-1] /yr	F_{CP} (2)
Unlikely	[0.0001-0.01] /yr	F_{CP} (3)
Very unlikely	[0.000001-0.0001] /yr	F_{CP}(4)
Remote	[0.00000001-0.000001] /yr	F_{CP}(5)

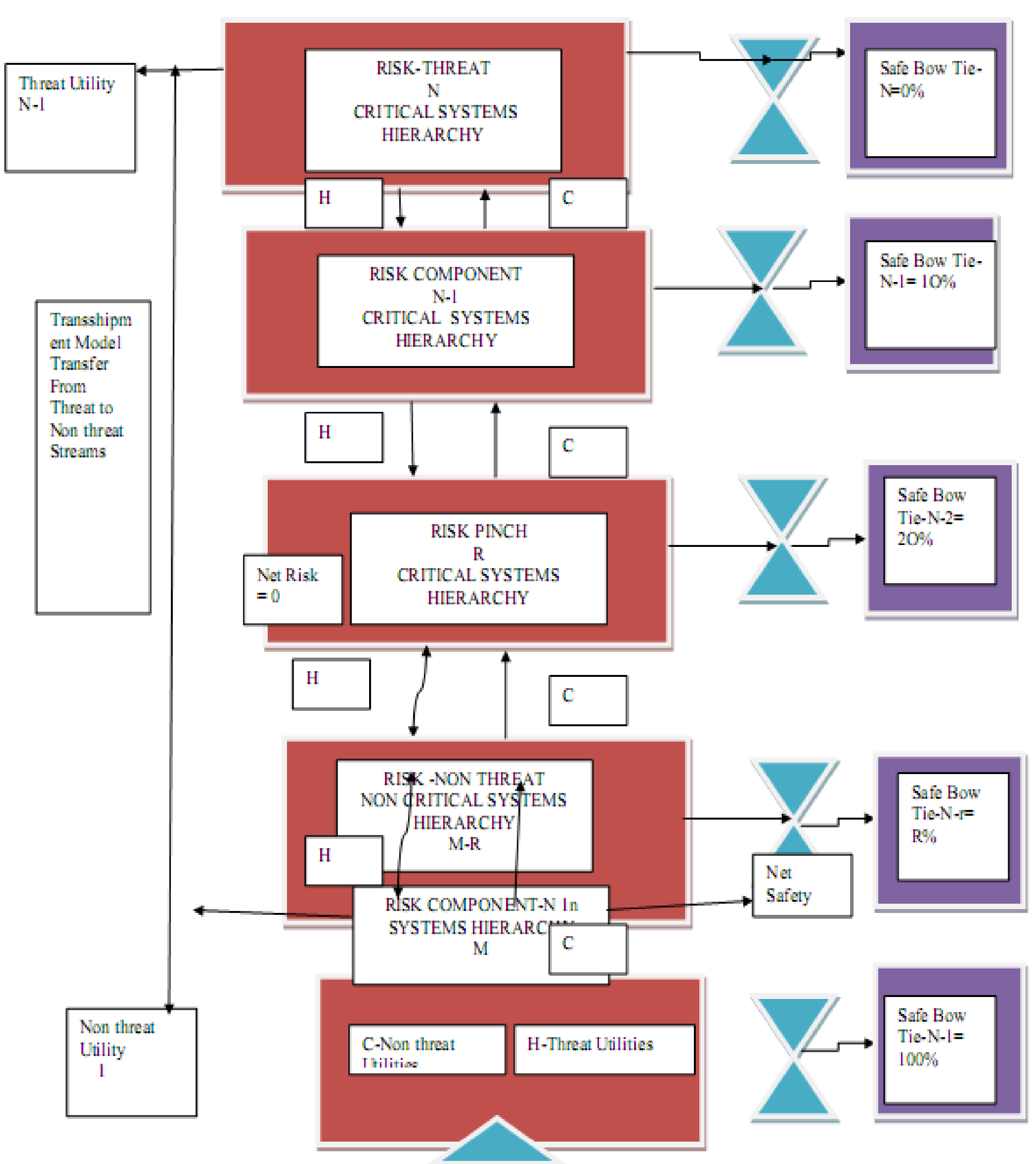

Figure 1: Transshipment Model for Transfer of threats Across Board

III. Application on Bow Tie System for FPSO

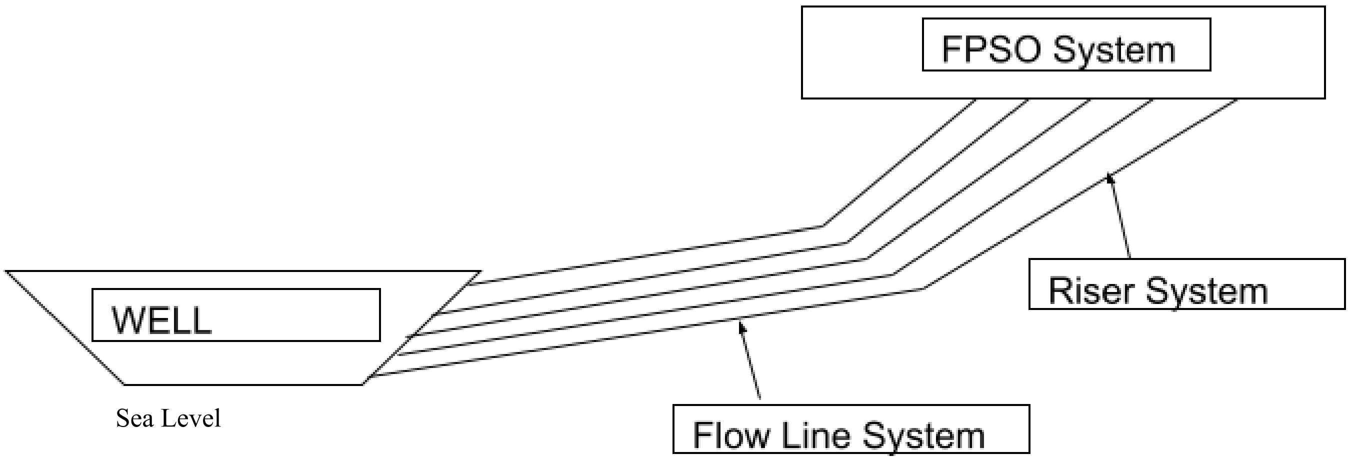

Figure 2: FPSO with riser and Flow lines

The FPSO above is typically a representative model of one currently operated by Multinational Oil Company in the Nigerian Deep Waters. The major hazards are identified in Figure 3.0 of the Bow Tie System constructed for purpose.

Fatalities

Process Worker on FPSO

5.76x 10 -4 fatalities per year.

-Ship crew worker on FPSO

4.19x 10 -4 fatalities per year.

Accommodation Worker on FPSO

3.70 x 10 -4 fatalities per year.

Process worker on platform

(Overnight on FPSO)

458 x 10 -4 fatalities per year.

The major accidents leading to loss in containment falls in two classes: 1) Technical and/or operational failure 2) Human and organizational errors such as Man and machine interface, the availability and effectiveness of operational, procedures which directly affects personnel performance (stress, system understanding, tiredness, etc.). Technical and operational failures are products of designs, age, operations, process and environmental failure factors. Human and Organizational Factors (HOF) is based on general industry practices which have the following elements: People, equipment (e.g. hardware), management systems, culture and environment. Equipment, people and management systems are shown as elements within the framework created by culture and environment. Examples of management systems include procedures, communication, training, management of change, risk assessment. Repair or Safety measures considered for FPSO, off-loading to shuttle tanker, supply and cargo vessels.

IV. Computational Analysis: Pinch to Construct Problem Table

The Problem Table, Grand Risk Composite Curves, Safety Targets and the Transshipment Model. The HAZARD data associated with the FPSO is computed from an Excel Programming provided in Table 1.0

a) *Design of the Risk Minimization Problem*

The basic principles of the pinch method [6] below represents further illustration and its application to risk minimization and safety targeting.

b) *Synthesis, Modelling and Design*

The Bow Tie diagram of operating FPSO is shown in Figure 1. A feasible design is to analyze the components separately. Nevertheless, we have only presented analysis for the RENS (Risk Exchanger Network Synthesis) and STNS (Safety target network synthesis) of Bowtie system of an operating FPSO.

For the RENS problem, the following data are required (7)

- A set of risk-threat streams to be cooled and a set of risk-non threat process streams to be heated.
- The hazard rates and the risk and safety targets of all process streams
- The safety weight capacities of each of risk streams versus their hazard rates as they pass through the heat exchange process.
- The available safety utilities, and index of performance in risk reduction and their costs per unit of heat provided or removed.

For the STNS problem, the following data are required

- A set of risk process streams generated and a set of risk targets streams
- The hazard rates and their risk status and risk targets

- The risk critical systems and risk non critical systems.
- Available end pipe treatment facility, their efficiency and cost per unit waste generated.

c) Analysis of the Problem Table FOR Safety targets Δγmin at 0% to 100%

The objective of the risk management problem is to minimize threats to personnel by applying a safety targeting technique. A typical Bowtie system contains a hazard stream of several threat levels and safety controls required to contain release to the environment. For our analysis, we have two kinds of stream, the risk threat and risk non threat streams. Therefore, the RENS problem for the bow TIE for risk threat and risk non threat streams. The minimized risk simulated for the personnel on FPSO set safety targets are γT1 (0%).γT2 (10%). γT3 (50%) γT4 (80%).γT5 (90%) from a normal operating targetγ. Change in risk reduction is by altering the operating variables, such that we can achieve 10%, 50%, 80% and 90% risk targets an extended table shown in Table 2, Table 3, and Table 4 can be developed. The target interval is subdivided into sub intervals with a minimum Δ γmin =0.1.

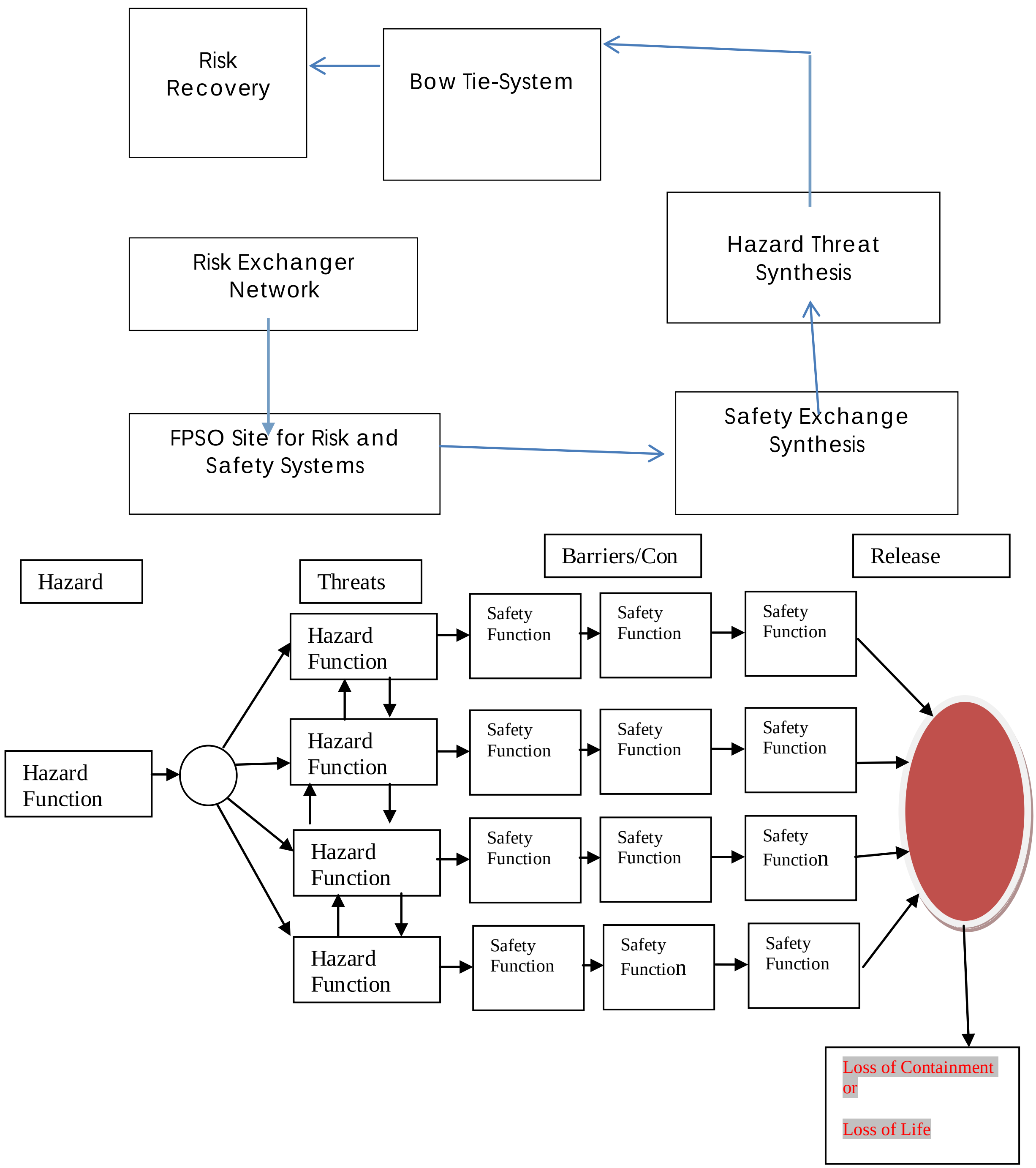

Figure 3: BOW TIE System of an FPSO

d) Hazard/Risk/Safety Targeting/Problem Table

The risk management problem table was derived by setting the non threat streams and the threat streams as follows:

THREAT STREAM

Hazard Class	Hazard Rate	Hazard Class
Definite to	[>10]/yr	FCP (0)
Very likely	[>1-10] /yr	FCP (1)
Likely	[0.01-1] /yr	FCP (2)

NON THREAT STREAMS

Hazard Class	Hazard Rate	Hazard Class
Unlikely	[0.0001-0.01] /yr	FCP(3)
Very unlikely	[0.000001-0.0001]/yr	FCP(4)
Remote	[0.00000001-0.000001] /yr	FCP(5)

The pinch for safety status for process worker on an FPSO in Table 2 to be γT1 (0.553733), γT2 (0.49836), γT3 (0.276867), γT1 (0.110747), and γT2 (0.055373), for 100%, 90%, 50%, 20%, and 10% safety targets respectively. As the safety targets is increased, the pinch point moves through a maximum. Minimum risk reduction stipulates that any streams above the pinch point represent the risk source, while any stream below the pinch represents risk sinks. As the pinch point, moves upward or as more of risk is reduced, the desired risk target objective. This is represented mathematically as Jacobean. As shown below there are four stream and the safety targets weights are:

RH= Risk Threat

RC= Risk Non threat

There are threat risk streams and two non threat risk streams. The hazards on the process worker on the FPSO Platform were considered for threat risk and hazards on the ship crew and accommodation worker is considered non threat streams

Risk-Safety and Hazard Stream Interval Table

The pinch analysis concept maximize the risk reduction between risk threat and risk non threat streams: There are four hazard classifications

$$JP = \left(\frac{\partial r}{\partial S}\frac{\partial S}{\partial h}\right)\langle\rangle\langle R\rangle_{\max imum} \quad (8)$$

The evaluation of available risk status for any interval can be given by the formula

$$R = \left(\frac{(\gamma_{T2}-\gamma_{T1})_{design}}{(\gamma_T-\gamma)_{operating}}\right) x R_O \quad (9)$$

$$S = 1 - R \quad (10)$$

Where

$$R\min = 1 - EXP(-\lambda\omega t) \quad (11)$$

Rmin is the minimum risk problem that needs to be targeted in our case, the risk on the process worker, accommodation and crew work. R and S are the design risk, and design safety respectively. Rmin minimum risk status respectively. $(\gamma_T - \gamma)_{\text{w operating}}$ and $(\gamma_T - \gamma)_{\text{w operating}}$ are the risk and safety interval respectively. The available risk or safety is evaluated as the total risk or safety available within a design interval. Hence, in table 2 for The pinch point for safety status for process worker on an FPSO in Table 2 to be γT1 (0.553733), γT2 (0.49836), γT3 (0.276867), γT1 (0.110747), and γT2 (0.055373), for 10%, 20%, 50%, 80%, 90%.

The Risk Transshipment at any point in Time is given for 100% to 90% safety target interval for a Process Worker on an FPSO

$$R = \left(\frac{0.553733 - 0.49836}{0.49836 - 0.42305019}\right) R_{\min} \quad (12)$$

$$R_{\min} = (1 - EXP(0.01 * 0.55373))T \quad (13)$$

The pinch analysis concept requires maximizing the risk reduction between risk threat and risk non threat streams.

V. Results and Discussions

a) Hazard weight data correlation table

Table 1.0 is a typical safety target table for assessing the complex multifunctional risk systems. The system linguistic class of component uses a weight index to measure multifunctionality and safety systems implemented. The risk index to quantify the levels of threats and the belief index to quantify an expert assignment of the certainty of risk in that systems. These qualifications and quantifications are important to classify the risk.

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Table 1.0: Typical Risk and Safety Table

Hazard Class Log in No.	Weight index	Safety Index	Hazard Rate	Risk Index	Risk Target
j1	w_1	s_1	h_1	r_1	ε_1
j2	w_2	s_2	h_2	r_2	ε_2
j3	w_3	s_3	h_3	r_3	ε_3
j4	w_4	s_4	h_4	r_4	ε_4
j5	w_5	s_5	h_5	r_5	ε_5
j6	w_6	s_6	h_6	r_6	ε_6
j7	w_7	s_7	h_7	r_7	ε_7

Table 2.0, Table3.0 and Table 4.0 which are the weight index data for hazard class of type 1, type2 and type 3 respectively has a classification of very likely to occur; for different safety fraction; for different hazard shape constant. We determine that the increase in numerical qualification of safety is significantly related to weight index as measure of such for specific hazard class and hazard shape function.

Table 2.0: Weight Data for Bowtie Hazard Rate for Hazard Class 1

Hazard Class 1	Weights Associated With Each Safety Fraction And Hazard Shape Function Constant											Max Safety
		Safety Index										
	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	0.9
Hazard Shape												
0.1	0.20487	0.1843847	0.163898	0.1434103	0.12229	0.102436	0.0819487	0.061462	0.0409744	0.0204872	0	0.02049
0.2	0.157793	0.1420135	0.126234	0.110455	0.09468	0.078896	0.063117	0.047338	0.0315586	0.0157793	0	0.01578
0.4	0.18720901	0.1684881	0.149767	0.1310463	0.11233	0.093605	0.0748836	0.056163	0.0374418	0.0187209	0	0.01872
0.6	0.296145	0.266531	0.236916	0.207302	0.17769	0.148073	0.118458	0.088844	0.059229	0.029615	0	0.02962
0.8	0.527031	0.474328	0.421624	0.368921	0.31622	0.263515	0.210812	0.158109	0.105406	0.052703	0	0.0527
1	1.00045	0.900405	0.80036	0.700315	0.60027	0.500225	0.40018	0.300135	0.20009	0.100045	0	0.10005
1.2	1.978261	1.780435	1.582609	1.384783	1.18696	0.989131	0.791305	0.593478	0.395652	0.197826	0	0.19783
1.4	4.023522	3.62117	3.218818	2.816466	2.41411	2.011761	1.609409	1.207057	0.804704	0.402352	0	0.40235
1.6	8.353799	7.518419	6.683039	5.847659	5.01228	4.17	3.34152	2.50614	1.67076	0.83538	0	0.83538
1.8	17.6198	15.857823	14.09584	12.333862	10.5719	8.809901	7.0479212	5.285941	3.5239606	1.7619803	0	1.76198
2	37.62817	33.86535	30.10254	26.339719	22.5769	18.8141	15.051268	11.28845	7.525634	3.762817	0	3.76282

Table 3.0: Weight Data Bow Tie Hazard Rate Computation for Hazard Class 2 for different hazard shape index values

Hazard Class 2= Likely to occur	Weight Index associated with each safety index				
0.553484076	Safety index				
Hazard Shape index	Safety index=0	Safety index=0.1	Safety index=0.5	Safety index=0.8	Safety index=0.9
0					
0.1	0.82422	0.741798	0.41211	0.164844	0.082422
0.2	0.50925	0.458325	0.254625	0.10185	0.050925
0.4	0.388808	0.349928	0.194404	0.077762	0.038881
0.6	0.395803	0.356223	0.197902	0.079161	0.03958
0.8	0.4532894	0.4079605	0.226644712	0.090657885	0.045328942
1	0.553733	0.49836	0.276867	0.110747	0.055373
1.2	0.704619	0.634157	0.352309	0.140924	0.070462
1.4	0.922237	0.830013	0.461118	0.184447	0.092224
1.6	1.232212	1.108991	0.616106	0.246442	0.123221
1.8	1.672506	1.505256	0.836253	0.334501	0.167251
2	2.298504	2.068653	1.149252	0.459701	0.22985

Table 4.0: Weight index data for hazard rate simulation for Hazard Class 4

Hazard Class 4= Very Unlikely to Occur	Weight Index Associated with Each Safety Fraction				
5.03E-05	Safety Index				
Hazard Shape Index	Safety index=0	Safety index=0.1	Safety index=0.5	Safety index=0.8	Safety index=0.9
0.1	3.25E-01	2.93E-01	1.63E-01	6.50E-02	3.25E-02
0.2	7.92E-02	7.13E-02	3.96E-02	1.58E-02	7.92E-03
0.4	9.40E-03	8.46E-03	4.70E-03	1.88E-03	9.40E-04
0.6	1.49E-03	1.34E-03	7.44E-04	2.98E-04	1.49E-04
0.8	2.65E-04	2.39E-04	1.33E-04	5.30E-05	2.65E-05
1	5.04E-05	4.53E-05	2.52E-05	1.01E-05	5.04E-06
1.2	9.97E-06	8.97E-06	4.98E-06	1.99E-06	9.97E-07
1.4	2.03E-06	1.83E-06	1.01E-06	4.06E-07	2.03E-07
1.6	4.22E-07	3.79E-07	2.11E-07	8.43E-08	4.22E-08
1.8	8.90E-08	8.01E-08	4.45E-08	1.78E-08	8.90E-09
2	1.90E-08	1.71E-08	9.51E-09	3.80E-09	1.90E-09

b) Analysis of the Problem Table for Safety targets $\Delta\gamma min$ at 0% to 100%

The objective of this study is to minimize the risk to personnel worker on an FPSO platform through a risk targeting technique employing pinch as shown in Table1.

Table 5.0: Typical Data

	Typical Data	FPSO Based Production Facility Case study			
Analysis	Process Worker (PF) on Platform	Process Worker (FP)	Ship Crew Worker (FP)	Accommodation Worker (FP)	
Hazard Class	Very Likely	Likely	Unlikely	Very Unlikely	
Hazard Stream	Risk-Threat	Risk-Threat	Risk-Non threat	Risk-Non threat	
Hazard Class No	J=1	J=2	J=3	J=4	

Table 5.0 is a table of the risk problem, determined as how impact of risk on personnel worker on FPSO can be reduced on minimized. A Bowtie systems contain a hazard stream, which produces several threat streams and safety controls to prevent release on containment. For our analysis, we have two kinds of stream, the risk threat and risk non threat streams. The risk, safety targets, risk targets or risk reduction of a FPSO, ship crew, accommodation worker and process worker on a platform. So, the RENS problem for the bow TIE can be formulated into risk threat and risk non threat. The objective is to minimize the risk on the personnel on FPSO. These can be achieved by setting out safety targets $\gamma T1$ (0%). $\gamma T2$ (10%). $\gamma T3$ (50%) $\gamma T4$ (80%). $\gamma T5$ (90%) from a normal operating targetγ. Assuming also it is possible to change risk reduction by altering the operating variables, such that we can achieve 10%, 50%, 80% and 90% risk targets an extended table shown in Table 2, Table 3, and Table 4 can be developed. The target interval is subdivided into sub intervals with a minimum Δ γmin =0.1. The pinch technique was applied to analyze risk to the personnel on FPSO. The pinch point for safety status for process worker on an FPSO in Table 2 was computed to be $\gamma T1$ (0.553733), $\gamma T2$ (0.49836), $\gamma T3$ (0.276867), $\gamma T1$ (0.110747), and $\gamma T2$ (0.055373), for 100%, 90%, 50%, 20%, and 10% safety targeting respectively. The design targets increases, the pinch point moves through a maximum. Minimum reduction, any streams above the pinch point represents the waste source, while any stream below the pinch represents risk sinks. The pinch point moves upward until desired risk target is achieved. The design that achieve minimize risk from the BOWTIE unit is realized when the Jacobean of the pinch point with respect to operating variable hazard rates favors movement such that maximum risk event occurs.

Table 6.0: Problem Table at 50% risk target

Hazard Classifications (fatalities/yr)	Stream Type	Safety Target 0%	Safety Target 50%	Weight Load Minimum	Safety SHIFTED 0%	Safety SHIFTED 50%	Hazard Rate Minimum	Risk Status	Risk Target 50%	Risk Reduction 50%
Very Likely [>1-10]/yr	Risk-Threat	1.00045	0.500225	0.100045	0.900405	0.40018	1	0.99591323	0.936151201	0.059762028
Likely [0.01-1]/yr	Risk-Threat	0.553733	0.276867	0.055373	0.49836	0.221494	0.01	0.42305019	0.141249497	0.281800692
Unlikely [0.0001-0.01]/yr	Risk-Non threat	0.005004	0.002502	0.0005	0.004504	0.002002	0.0001	0.00503727	1.2635E-05	- 0.005024635
Very Unlikely [0.000001-0.0001]/yr	Risk-Non threat	5.04 E-05	2.52E-05	0.00000504	0.00004536	2.02E-05	0.0000001	5.0499E-05	1.2726E-08	-5.05E-05

Table 7.0 is the risk extended problem table. The table shows the minimum safety target (0%) which can be increase to a safety target of 50%. The hazard rate minimum for the process worker on the platform, process worker on FPSO, ship crew and accommodation is 1, 0.01, 0.001, and 0.0000001 fatalities per year based on the hazard classification very likely, likely, unlikely, very unlikely. This is a reduction in risk target as the safety target is increased from 0% to 50%.

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The pinch analysis concept allows us to maximize the risk reduction between risk threat and risk non threat streams: There are four hazard classifications

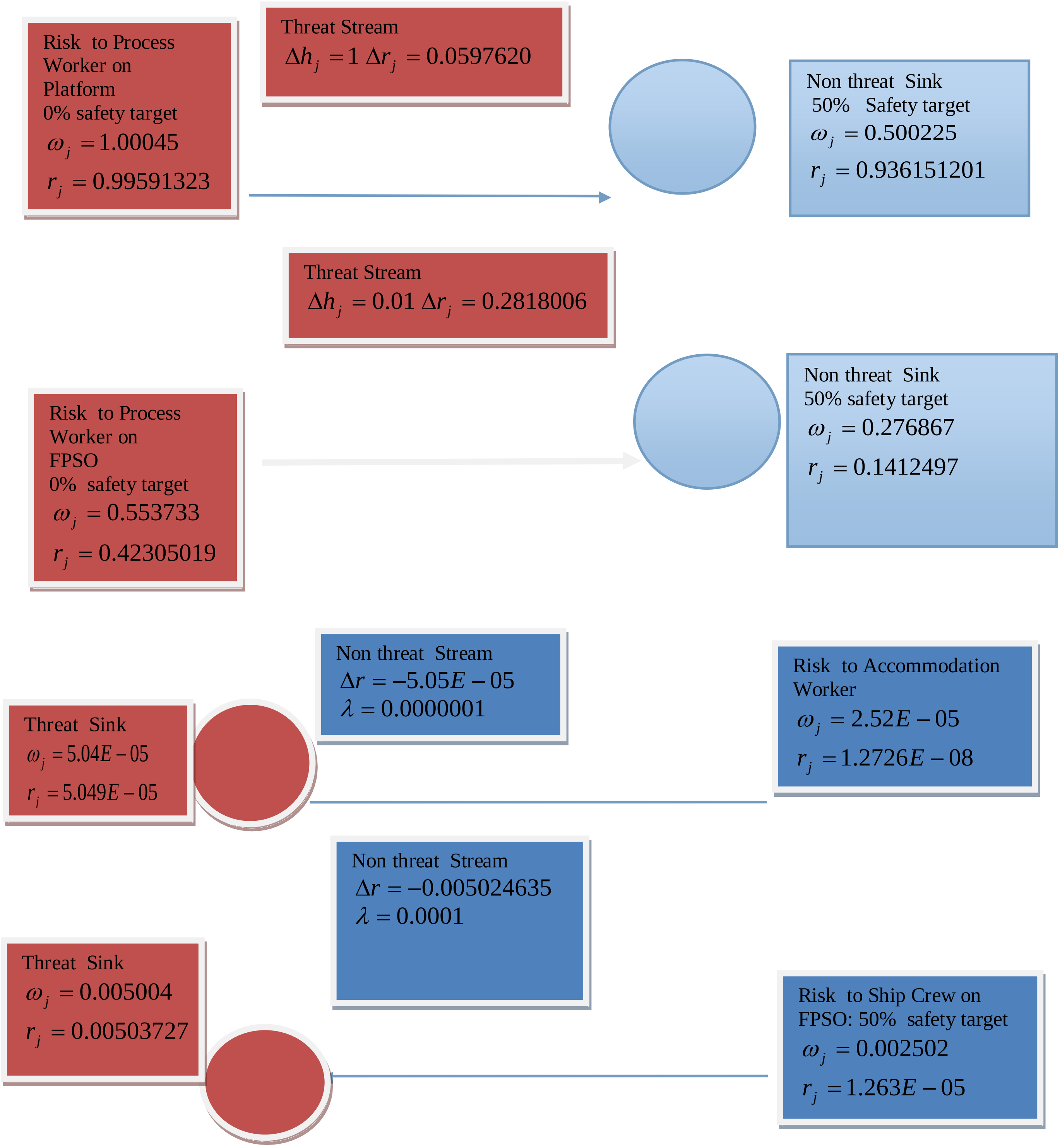

Figure 4: Diagram Design Interval

The risk to the accommodation worker and ship crew are 1.2726E-08 and 1.263E-05 respectively. The level of critical safety systems deployed on these personnel is small and could be referred in our model as non threat sink. The process worker that is exposed to more critical risk is referred as the threat sink on the FPSO and targets is to reduce the threats from 0.996 and 0.4234 by deploying resources allocated to non threats sink (accommodation and ship crew) to the threat sink (process worker) to minimize the risk and threat levels on these personnel.

Table 7.0: Risk-Safety/Hazard Stream–Extended Table

Hazard Classifications (fatalities/yr)	Stream Type	Hazard Rate Minimum	Risk Status	Risk Target 50%	Risk Reduction 50%	Extended Table Problem PINCH DESIGN INTERVAL	Cascade
Very Likely [>1-10]/yr	Risk-Threat J=1	1	0.99591323	0.936151201	0.059762028	0	0.054737393
Likely [0.01-1]/yr	Risk-Threat J=2	0.01	0.42305019	0.141249497	0.281800692	1	0.276776057
Unlikely [0.0001-0.01]/yr	Risk-Non threat J=3	0.0001	0.00503727	1.2635E-05	-0.005024635	(PINCH PT) 2	0
Very Unlikely [0.000001-0.0001]/yr	Risk-Non threat J=4	0.0000001	5.0499E-05	1.2726E-08	-5.05E-05	3	0.004974135

For the risk target is 50% and 0%, the pinch point is located at interval 2. The risk threat streams are required to cool and the safety sinks is increased, and non threat streams require heat by non critical risk. There is a risk reduction above the pinch and a reversal below the pinch. The pinch is located for the ship crew that is classified as non threat stream.

Table 8.0: Hazard/Risk Reduction Table

Threat To: Risk System	Hazard Classifications (fatalities/yr)	Stream Type	Risk Reduction 100%	Risk Reduction 90%	Risk Reduction 50%	Risk Reduction 20%	Risk Reduction 10%
Process Worker on FPSO	Likely [0.01-1]/yr	Risk-Threat	0.16050302	0.18330776	0.281800692	0.36395731	0.3930541
Ship Crew Worker	Unlikely [0.0001-0.01]/yr	Risk-Non threat	0.00501182	0.00501453	0.005024635	0.00503222	0.0050347
Accomodation Worker	Very Unlikely [0.000001_0.0001]/yr	Risk-Non threat	5.0473E-05	5.0476E-05	5.0486E-05	5.0494E-05	5.05E-05
Process Worker on Platform	Very Likely [>1-10]/yr	Risk-Threat	0	0.00298088	0.059762028	0.32861958	0.5727203

c) Risk Reduction Curve/Risk Status with Safety Targets

The safety composite graphs are shown in Figure 4 and Figure 5. Risk target and risk reduction are below the design risk status for the personnel work showing a reduction in risk as the safety sink increases.

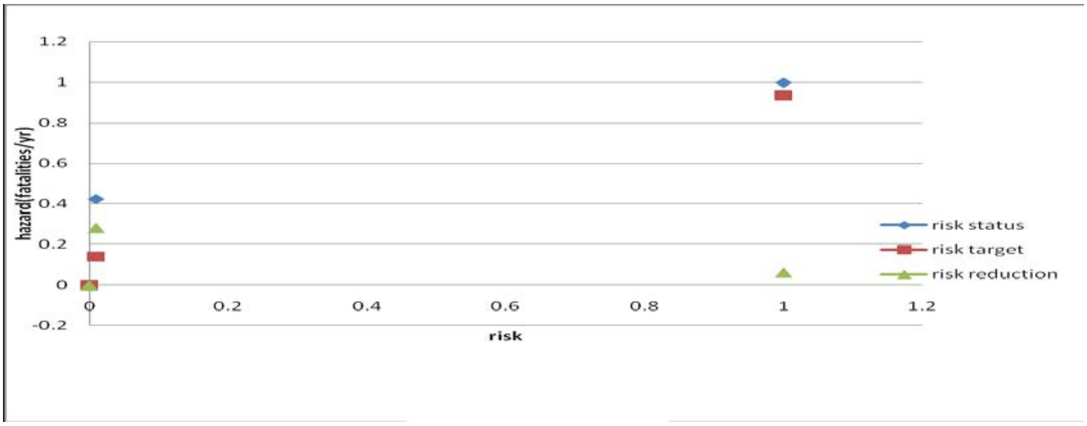

Figure 4: Problem Table on Risk Reduction: Composite Curve

Figure 5.0 show a progressive reduction below the 0% safety classification that is for 10%, 50%, 80%, 90% target, shows a risk target below the design safety for personnel on the platform.

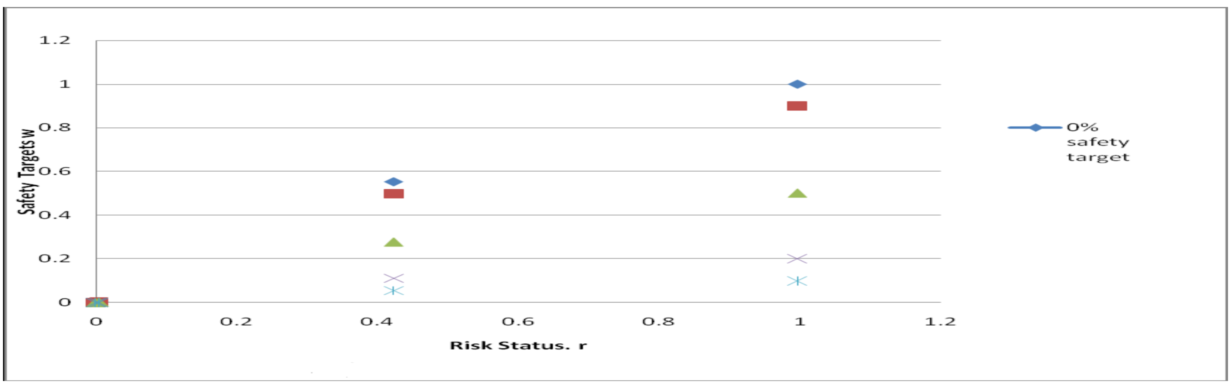

Figure 5: Plot of risk Status with Safety Targets

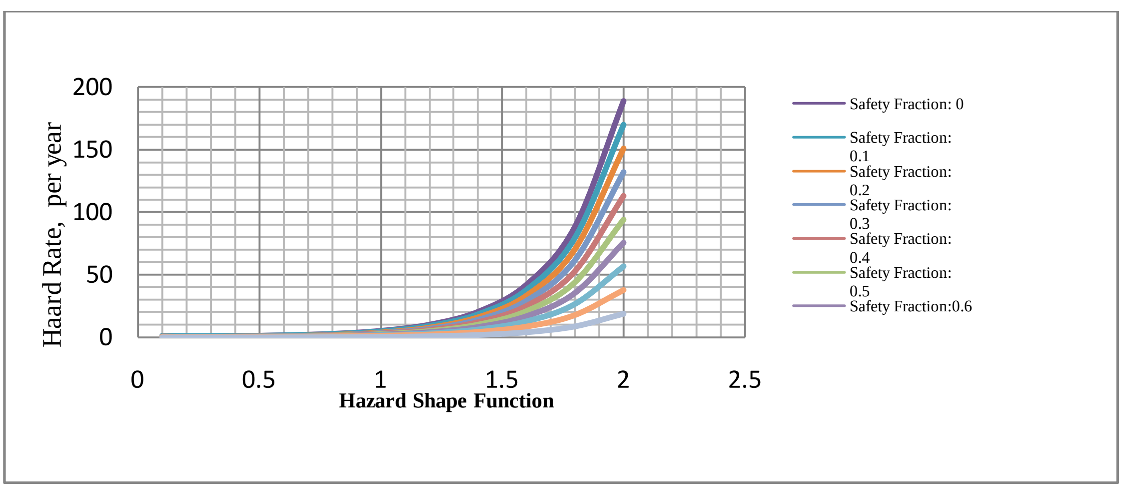

Figure 6: Hazard Rate with Hazard Shape Index for Fuzzy Class 1 for different Level of Safety

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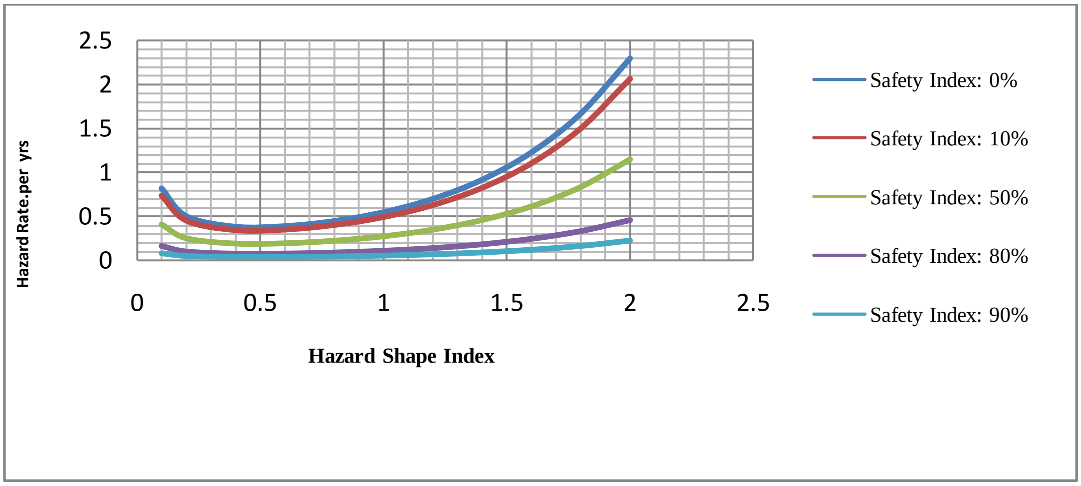
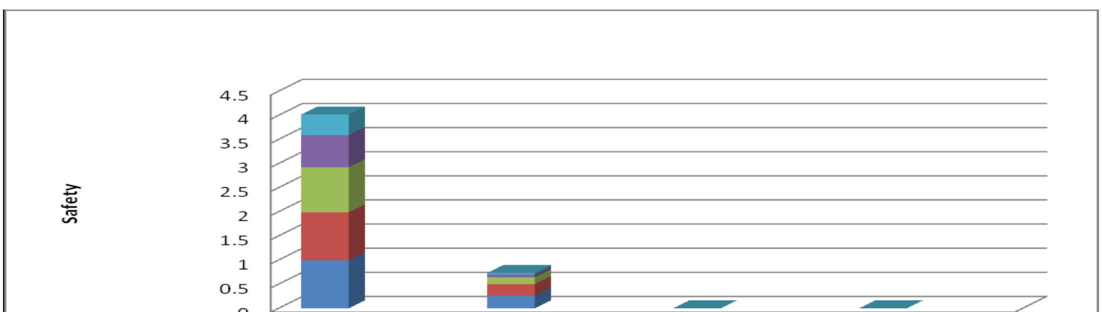


Figure 7: Plot of Hazard Rate with Hazard Shape Index for different Level of Safety for Fuzzy Class 2

Figure 6 shows the simulated hazard rate for hazard class 1, while Figure 7 shows the simulated hazard rate for hazard class 2 for the personnel worker. The hazard class 1 qualification as unlikely to occur appears to reduced as improve safety index are increased from 10% to 90%.

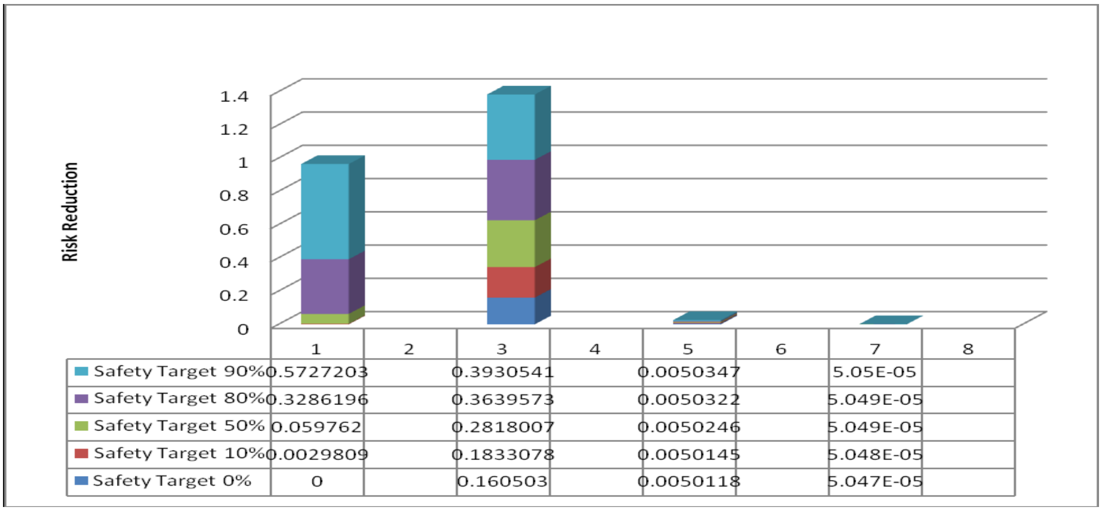
d) The Plots of Hazard Rate for different Hazard Class and Safety Index

Figure 8 and Figure 9 shows that Risk Status/ Risk Reduction Bar Chart. Whereas it is clear from Figure 8 that the safety is highest for the 90% safety and least for the 0% safety. Also the Process worker on platform and FPSO seem to exhibit the greatest Risk Target, while the accommodation and ship crew worker exhibited lesser risk target.



	1	2	3	4	5	6	7	8
90% safety target	0.423193		0.0299961		2.525E-06		2.545E-09	
80% safety target	0.6672936		0.0590929		5.055E-06		5.101E-09	
50% safety target	0.9361512		0.1412495		1.264E-05		1.273E-08	
10% safety target	0.9929324		0.2397424		2.274E-05		2.288E-08	
0% safety target	0.9959132		0.2625472		2.545E-05		2.545E-08	

Figure 8: Bar Chart of Risk Target



	1	2	3	4	5	6	7	8
Safety Target 90%	0.5727203		0.3930541		0.0050347		5.05E-05	
Safety Target 80%	0.3286196		0.3639573		0.0050322		5.049E-05	
Safety Target 50%	0.059762		0.2818007		0.0050246		5.049E-05	
Safety Target 10%	0.0029809		0.1833078		0.0050145		5.048E-05	
Safety Target 0%	0		0.160503		0.0050118		5.047E-05	

Figure 9: Bar Chart of Risk Reduction

Figure 9 shows that risk reduction bar chart shows that risk reduction for safety index of 0% and highest at the maxum safety index of 90% on process worker on FPSO and Platform are impacted with the most risk threat.

e) Plot of Belief Variable for Hazard class 1 at safety index 0% and safety index 90%

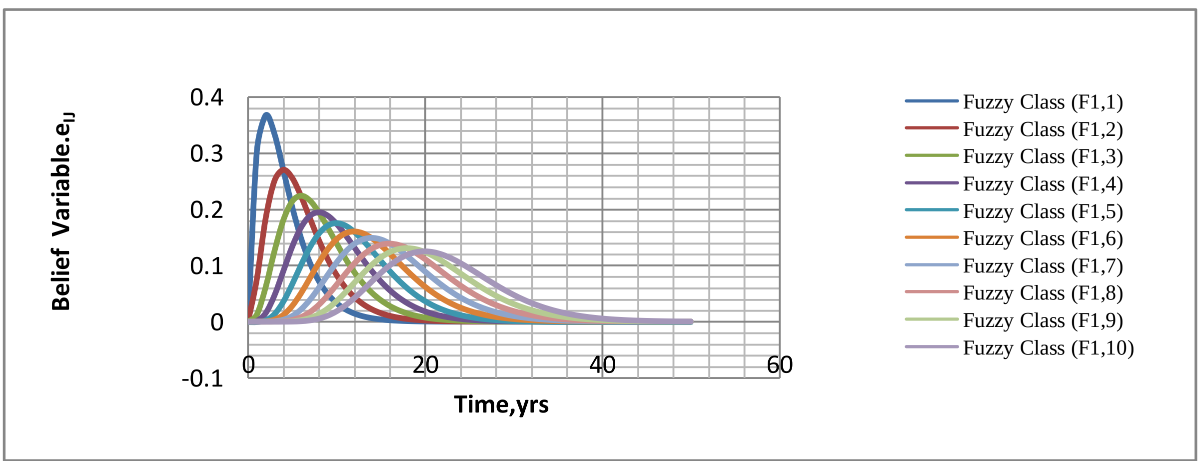


Figure 10: Plot of Belief Variable e_{ij} with Time (yrs) for hazard class 1 for 90% Safety index for different hazard shape =1.0 for no of failures 1-10 constant F1(1,-10)

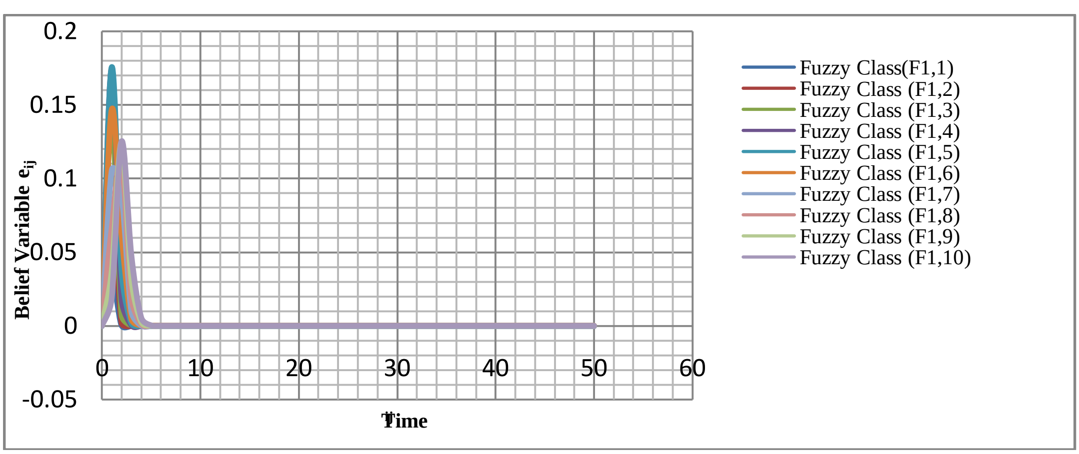


Figure 11: Plot of Belief Variable e_{ij} with Time (yrs) for hazard class 1 for 0% Safety index for hazard shape index =1.0 for no of failures 1 to 10 F1(1,-10)

Figure 10 is a plot of the belief index for hazard class 1 with 90% safety index which has a numerical classification as Very likely [>1-10] /yr assigned a value hazard set value $F_{CP}(1)$ .Figure 11 is the plot of belief variable (confidence level) where the safety index is 0% for a number of failures 1 to 10 for a when hazard shape index=1.0. The belief variable is a measure of the index of certainty that within a particular time, the probability of occurrence is high. The belief variable ε_{ij} represents the uncertainty an expert associates with an input data. For maximum safety index of 90%, the parabolic profile is more evenly spread with time than for the case with safe index of 0%, clearly indicating uncertainty on personnel worker depending on system would fail is higher for a system with lower safety index than a higher safety index.

f) Risk Variable for different Safety Index

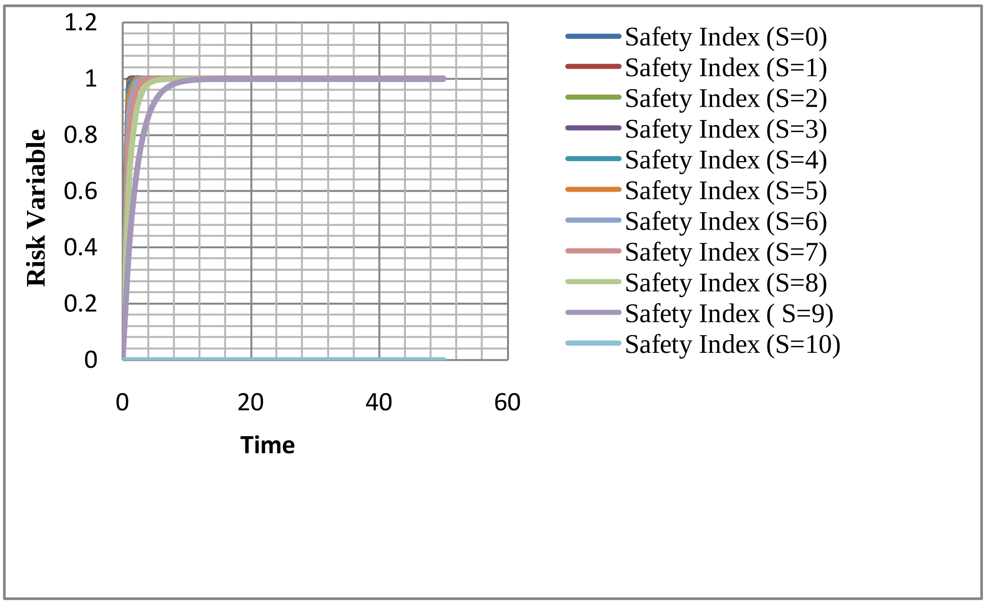


Figure 15: Plot of Risk Variable with Time for Different Safety Index for Fuzzy Class 1 Failures Hazarzd Shape function=1.0

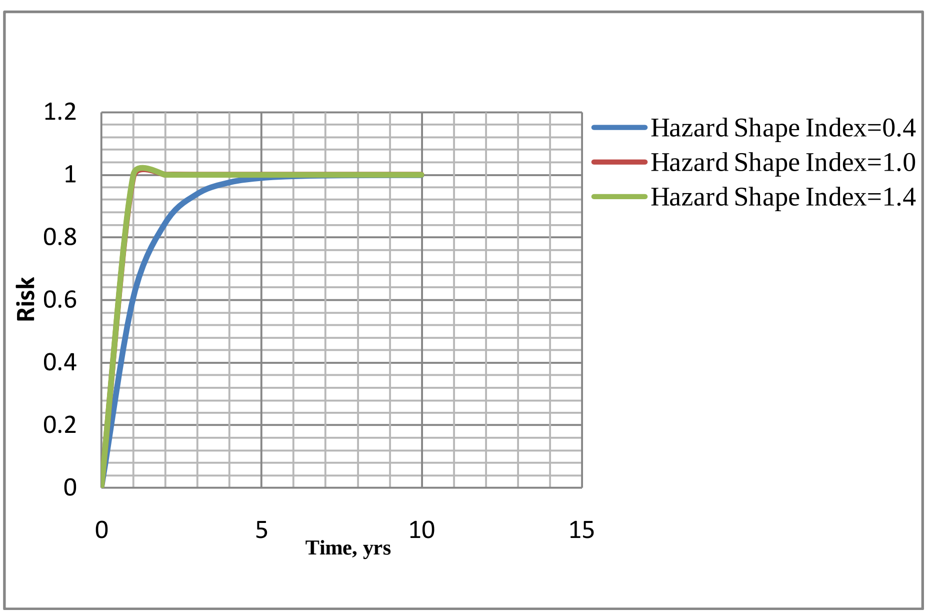


Figure 16: Risk with time for different shape index for 0% safety for fuzzy 1 class hazard

Figure 15 is the plot of the risk in a system with time in relationship to the safety index, for hazards class 1 type. The plot shows that risk of the FPSO's system increases exponentially with time but decreases as the safety index increases. Whereas Figure 16 showed exponentially increase of risk with time for safety that is

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non-existent 0% for all hazard indexes with the risk taking lesser values for lower hazard shape index.

VI. Conclusion

A model is presented to plan personnel safety on FPSO. Data was obtained from a multinational oil company operating in deepwater. Based on data obtained from a deepwater multinational oil and gas operator in Nigeria, personnel risk reduction on personnel is simulated as safety targets index increases from 0% to 90%. The plots of risk reduction /risk safety composite graph for risk target shows a risk reduction below the design risk status thresholds to plan credible threat reductions on personnel of complex process and production systems.

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The author acknowledges the support or SNEPCO (Shell Nigerian Exploration &Production Company Inc.) for access to data Information. The author appreciates colleagues especially Professor Alfred A. Susu at the University of Lagos for valuable contribution. The support of NAPIMS and NNPC staff for the support for this research work is also appreciated.

VII. Nomenclature

ω_i	Weight index
U_i	Risk or Reliability Factor
r_i	Risk potential
R_{si}	Reliability/Safety
λ_w	Hazard Rate (combined sum)
λ_{ws}	Hazard Rate (Combined Series Sum)
λ_{wp}	Hazard Rate (Combined Parallel Sum)
N	Number of Components
F1	Fuzzy Class (Very Likely)
F2	Fuzzy Class (Likely)
F3	Fuzzy Class (Unlikely)
F4	Fuzzy Class (Very Unlikely)
F5	Fuzzy Class (Remote)
SRfi	Safety Index
β_i	Hazard Shape Index
λ_{ij}	Hazard rate of i-component interacting with j component
λ_{im}	Hazard rate of combined mean
ϖ_{si}	Safety Weight Index
μ_{ij}	Repair rate

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Transitabilidad Peatonal en un Trecho de La Vía España con Edificios con Espacios de Transición: Cañón Urbano entre Plaza Regency y El Rey

By Eneida Sención, Isabel Saavedra, Kiamelys Rivera & Jorge Isaac Perén
Universidad de Panamá

Abstract- The walkability was studied in the urban canyon of the Vía España, in Panama City, between the Rey Supermarket, the pedestrian bridge, Plaza Concordia and Plaza Regency. The pedestrian analysis was based on the multivariate logic model. It was carried out with two cameras simultaneously filming both sides of the urban canyon of the Via España in a period of one hour (from 12:30 pm to 1:30 pm) from July 5, 2018 with the aim of quantifying the routes and deviations of pedestrians. 60% of the pedestrians passed through the transition spaces of the Plaza Regency sector and at the Rey supermarket sector, 85% of the pedestrians used the transition spaces of the building. In Plaza Regency, pedestrians make small deviations to walk within the shaded area (transition space), however in the Rey supermarket sector the flow of pedestrians has a continuous and well-defined path.

Keywords: walkability, pedestrian comfort, activity mapping, deviation, perception of the environment, route choice, urban canyon.

GJRE-J Classification: LCC: HE305.P2

TRANSITABILIDADPEATONALEN UNTRECHODELA VAESPAACONEDIFICIOS CONESPACIOSDETRANSICINCAN URBANOENTREPLAZAREGENCYYELREY

Strictly as per the compliance and regulations of:

Transitabilidad Peatonal en un Trecho de LaVía España con Edificios con Espacios de Transición: Cañón Urbano entre PlazaRegency y El Rey

Eneida Sención α, Isabel Saavedra σ, Kiamelys Rivera ρ & Jorge Isaac Perén ω

Resumen- Se estudió la peatonalidad en el cañón urbano de la Vía España, en la ciudad de Panamá, comprendido entre el Supermercado Rey, el puente peatonal, Plaza Concordia y Plaza Regency. El análisis de peatonalidad se basó en el modelo lógico de multivariantes. Se realizó con dos cámaras filmando simultáneamente ambos lados del cañón urbano de la Vía España en un período de una hora (de 12:30p.m. a 1:30p.m.) del día 5 de julio de 2018 con el objetivo de cuantificar los trayectos y desviaciones de los peatones. Entre el 60% y el 85% de los peatones caminaron por los espacios de transición o aceras perimetrales a los edificios del sector de la Plaza Regency y del supermercado Rey, respectivamente. En la Plaza Regency los peatones realizan pequeñas desviaciones para caminar dentro del área sombreada (espacio de transición), sin embargo en el sector del supermercado Rey el flujo de peatones tiene un trayecto continuo y bien definido.

Palabras Claves: transitabilidad, comodidad del peatón, mapa de actividades, desviaciones, percepción del medio ambiente, ruta de elección, cañón urbano.

Abstract- The walkability was studied in the urban canyon of the Vía España, in Panama City, between the Rey Supermarket, the pedestrian bridge, Plaza Concordia and Plaza Regency. The pedestrian analysis was based on the multivariate logic model. It was carried out with two cameras simultaneously filming both sides of the urban canyon of the Via España in a period of one hour (from 12:30 pm to 1:30 pm) from July 5, 2018 with the aim of quantifying the routes and deviations of pedestrians. 60% of the pedestrians passed through the transition spaces of the Plaza Regency sector and at the Rey supermarket sector, 85% of the pedestrians used the transition spaces of the building. In Plaza Regency, pedestrians make small deviations to walk within the shaded area (transition space), however in the Rey supermarket sector the flow of pedestrians has a continuous and well-defined path.

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I. Introducción

Por muchos años se han investigado las afectaciones micro climáticas de la morfología urbana sobre los espacios públicos y, en dichos estudios, se usa el término cañón urbano para referirse a la calle o espacio público de vialidad delimitado por edificios contiguos alrededor [1, 2]. Los estudios recientes indican que el microclima de un cañón urbano se ve ampliamente afectado por el acceso solar y las condiciones de sombra [2]. Los espacios de transición de tipo exterior o de galerías, tienen la ventaja de proveer a los peatones de lugares sombreados, ya que un espacio de transición es una zona multifuncional que conecta las áreas interiores y exteriores de un edificio [3]. Los espacios sombreados y de actividad comercial, son factores que favorecen la vitalidad de una zona [4]. Para un caso de actividades comerciales a ambos lados de la calle, otro estudio apuntó a que la morfología urbana como el cerramiento, la longitud del bloque y las condiciones del borde fueron fundamentales para crear la percepción de un vecindario transitable [5]. Cada uno de estos factores afecta la vitalidad del lugar y determinan las elecciones de rutas por parte de los peatones [6, 17, 18]. En este mismo estudio se conocen modelos que miden a través del levantamiento de la infraestructura urbana la transitabilidad de un lugar, como el Modelo lógico de multivariantes *(Multivariate logit model)* que rompe la idea tradicional, declarando que el peatón no solo elige una ruta por su distancia sino por los factores físicos como: comercios, vegetación, cerramientos, y factores psicológicos como la seguridad, los vacíos, etc.

Transitabilidad es la relación del peatón con el entorno construido [11]. Esta investigación mapea los flujos de peatones y la transitabilidad en un trecho de la Vía España, comprendido entre el puente peatonal diagonal al supermercado el Rey y la Plaza Regency. Estos últimos frentes de edificios conforman un cañón urbano interesante de ser evaluado pues el estudio anterior de Alveo et al, 2017 [6] sólo se enfocó en la Plaza Regency. Alveo et al., 2017 realizó mediciones de peatonalidad en la Plaza Regency en dos periodos diferentes: (1) en la mañana del 30 de octubre de 2017 (de 7:30am a 8:20am) y (2) en la tarde del 31 de octubre de 2017 (5:00pm a 5:40pm). En dichos períodos, transitaron 760 y 877 peatones respectivamente, y en ambos más del 55% circularon por el espacio de transición o acera perimetral del edificio de Plaza Regency, próximo a los locales comerciales.

Author α σ ρ: Facultad de Arquitectura y Diseño, Universidad de Panamá, Ciudad de Panamá, Rep. de Panamá.
e-mails: sencion217.es@gmail.com, isabelsaavedra09@gmail.com, kiamelys10@gmail.com
Author ω: Sustainable Building and City Research Group - SusBCity, Ciudad de Panamá, Rep. de Panamá. e-mail: jorge.peren@ac.pa

En un clima tropical [13], como el caso de Panamá, Se debe prestar atención a la insolación directa y a la infraestructura verde de los espacios urbanos [14]. Algunos estudios resaltan el enfoque sistémico hacia las ciudades inteligentes, compactas y verdes; como parte de un desarrollo urbano planificado [15]. La planificación y el diseño para caminar son cruciales para promover una vida pública saludable, creando barrios, mejorando la vida social y la economía [5].

La cantidad de estudios referentes a la movilidad de peatones es limitado, especialmente en Panamá. En el contexto de desarrollo urbano de la ciudad de Panamá es fundamental desarrollar estudios e investigaciones que proporcionen datos cuantitativos y cualitativos sobre el comportamiento de los peatones en el entorno urbano. Al realizar una revisión de la literatura nacional sobre la peatonalidad se destacan algunos estudios enfocados en el entorno de edificios con espacios de transición [6-8] y otros en intersecciones y cruces de vías [9]. Entre ellos sólo se encontró una investigación cercana a la Plaza Regency realizada por Alveo et al., (2017) [6], en la cual los autores mapearon los trayectos de los peatones en las aceras internas y perimetrales externas de la Plaza Regency.

La zona seleccionada para este estudio cuenta con igual condición de aceras y de edificios con espacios de transición en ambas laterales del cañón urbano de la Vía España. Además, ambas laterales cuentan con similar intensidad de flujo peatonal consecuencia de ser un área con vitalidad urbana. Los resultados de esta investigación, y las condiciones de vitalidad y calidades del entorno urbano podrían futuramente co-relacionarse con los tipos de rutas y desviaciones de los peatones.

Los objetivos específicos de esta investigación son: (a) cuantificar la cantidad de peatones y su respectivo trayecto en un segmento del cañón urbano de la Vía España que comprende las aceras perimetrales del supermercado Rey y de la Plaza Regency, así como la acera paralela a dicha avenida; (b) aumentar el conocimiento general sobre la movilidad peatonal en Panamá; (c) caracterizar la morfología urbana del sitio y los principales factores urbanos y ambientales en dicho cañón urbano.

II. Metodología

Para este trabajo se realizó una breve revisión de la literatura, empleando la plataforma Science Direct (www.sciencedirect.com), donde se consultaron artículos científicos sobre transitabilidad urbana publicados en las mejores revistas indexadas.

a) Caso de estudio

La Vía España mantiene edificios adosados y presenta amplias servidumbres públicas, de entre 15m y 17m. A lo largo de la vía existe una tendencia de formación de un cañón urbano, el cual también se ocupa por edificios de negocios. Presenta una orientación solar este-oeste por lo cual ambas partes de la vía se ven afectadas por el sol. El segmento de estudio presente se enmarca entre el espacio público del Supermercado Rey de Vía España y el perímetro externo de la Plaza Regency, diseñada por Richard Holzert [16] (Fig. 1).

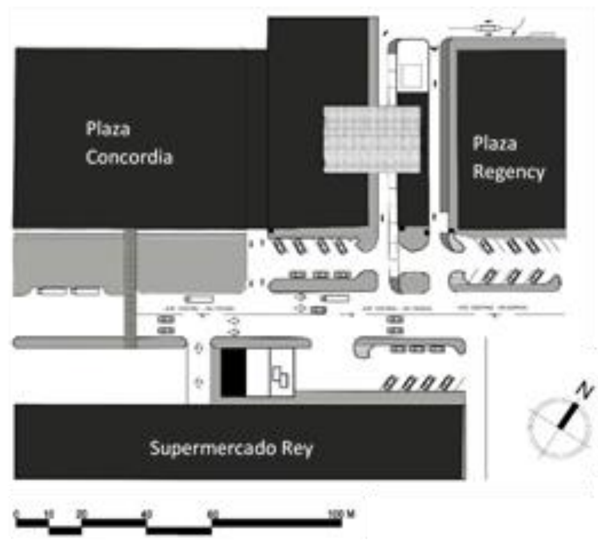

Figura 1: Vista en Planta, actualizada al 2018 de la Plaza Regency y Supermercado Rey.

b) Local y hora de las filmaciones

A la altura del puente peatonal de plaza Concordia se ubicaron dos cámaras de videos PC1 y PC2 (Fig. 2, 3,4) que grabaron simultáneamente por un período de una hora, de 12:30p.m. a 1:30p.m. el día 5 de julio de 2018. Este horario se consideró tomando en cuenta las horas de mayor sol. Se contaron las personas que ingresaban o pasan por el campo de visión de las cámaras (Fig. 5).

c) Infraestructura urbana

Siguiendo los parámetros del modelo lógico de multivariantes, este proyecto entra en la categoría de desviación débil y de continuación fuerte. Ya que las distancias de elección no sobrepasan los 40m. Se ha realizó la lectura del entorno en un radio de 500m para la mejor descripción del entorno del área estudiada (Ver tabla 1).

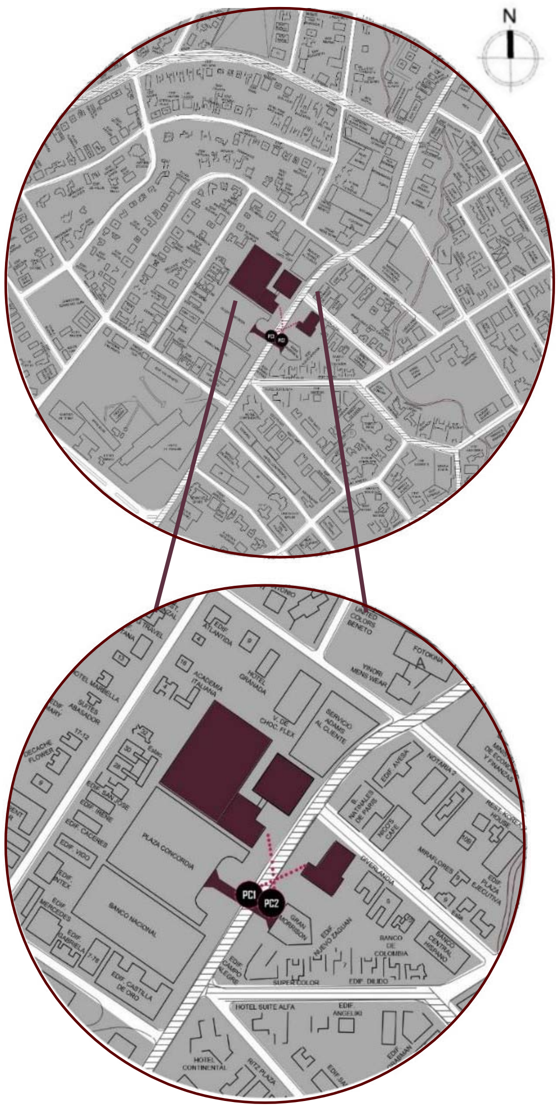

Figura 2: Mapa de Posición del área de estudio y de la posición de las cámaras en el puente peatonal sobre la Vía España

Figure 3: Encuadre y campo de visión para el Supermercado Rey

Figura 4: Encuadre y campo de visión de la cámara PC1 para el supermercado Rey y la PC2 para la Plaza Regency.

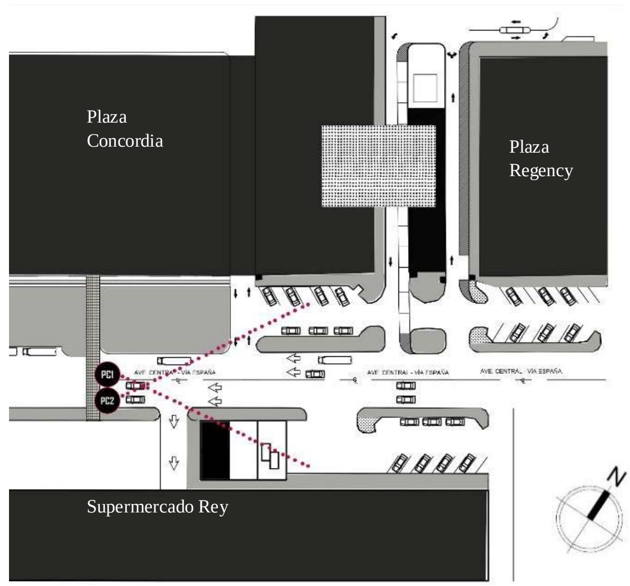

Figura 5: Posición de cámaras en los alrededores de la Plaza Regency y el Supermercado Rey

III. Resultados

a) Tendencias de trayectos y desviaciones de peatones

La figura 6 muestra la intensidad y trayecto de los peatones en el cañón urbano de la Vía España seleccionado para este estudio. Dentro del perímetro externo de la Plaza Regency, se observan cuatro (4) tendencias de trayectos: (1) por el espacio de transición, (2) por la parte trasera de los autos estacionados, (3) por las aceras adoquinadas paralelas a la Vía España y (4) cruce de la vía España. (Fig. 6,7). En el Supermercado Rey se observaron 3 tendencias de trayectos: (1) por el espacio de transición, (2) por las aceras adoquinadas paralelas a la Vía España y (3) cruce de la vía España. (Fig. 6,8).

i. *En el sector de la Plaza Regency*

En la Plaza Regency 60% de los peatones prefieren caminar en la acera techada (perimetral o espacio de transición del edificio) a pesar de tener que realizar desviaciones débiles; un 25% evita parcialmente estas desviaciones y atraviesan la plaza de estacionamientos; pero solo un 10% utiliza las aceras adoquinadas, de los cuales el 4% lo realizan para cruzar caminando la Vía España.

ii. *En el sector del Supermercado Rey*

En el Supermercado Rey 85% de los peatones utilizan la acera techada perimetral de dicho edificio (o espacio de transición). El 10% de los peatones caminan por la acera adoquinada, utilizando el eje de salida del puente peatonal; mientras que el 5% cruza la plaza de estacionamiento pues provienen de las aceras adoquinadas para desviarse hacia el espacio de transición del edificio.

b) Análisis según el modelo lógico de multivariantes

La actividad comercial con entradas desde planta baja favorece la vitalidad del lugar, la zona en este cañón urbano es muy ocupada por edificios de comercio que se puede apreciar en el uso de suelo (Fig. 9). Las altimetrías de estos edificios se caracterizan de 2 a 4 niveles, que le da una valoración positiva (Fig 10, 11). La movilidad urbana sugiere que el lugar tienda a comportarse de forma lineal (Fig. 12). La presencia de vegetación es escasa y es nula para el Supermercado Rey y este factor se valora negativamente (Fig. 13).

Estas características del sitio dan por resultado dos tendencias: la desviación débil y la continuación fuerte (Tabla 1). Las desviaciones débiles se reconocen en el perímetro de la plaza Regency, debido a la presencia de espacios confortables o de sombras, las personas tienden a realizar una caminata lineal a pesar de ser una distancia corta como se tenía previsto. En el Supermercado Rey se observó de forma concreta que las personas podían tener una marcha continua a lo largo del sitio, según el modelo lógico de multivariantes. A causa de la cantidad de carriles que presenta la zona de estudio las personas están obligadas por seguridad a pasar en los perímetros, y este flujo es cómodo ya que se ofrece un espacio de transición.

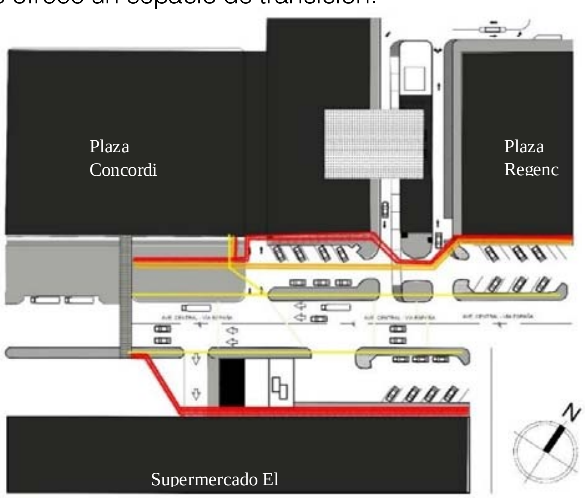

Figura 6: Mapa que muestra la Intensidad de peatón en la Plaza Regency y Supermercado Rey

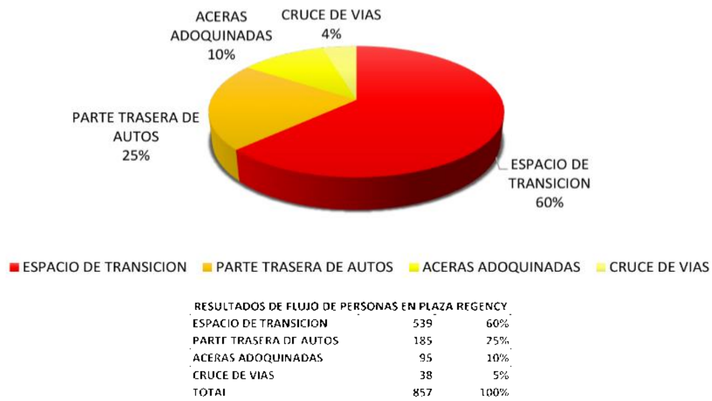

Figura 7: Intensidad de flujo peatonal de Plaza Regency

Figura 8: Intensidad de flujo Peatonal del Supermercado Rey

c) Mapas de Análisis de las infraestructuras del sitio

Tabla 1. Modelo Lógico Mutivariante

Desviación- Débil			
		Descripción	
Factor	**Valor**	**Regency**	**El Rey**
Comercios Pequeños	2	Almacenes (Adams y Collins)	Supermercado Rey
Flores	0	4 árboles pequeños	Ningún
Espacios Verdes	0	No hay	No hay
Altura de las Edificaciones	2	3-4 niveles	2 niveles
Cuadricula	2	Poco ortogonal	Poco ortogonal
Continuar - Fuerte			
Comercios Pequeños	1	No tiene pequeños puestos	Vendedores ambulantes, chanceros, vendedores de comida
Cuadricula	2	Poco ortogonal	Poco ortogonal
Cantidad de Carriles	-2	2 en un sentido más estacionamientos internos	2 en un sentido más estacionamientos internos

Escala de valoración de positivo a negativo	2	Tiene suficiente
	1	Solo un lado del area tiene sufiente
	0	Calificacion negativa para ambas partes
	-1	Solo un lado del área tiene demasiado
	-2	Ambos lados del área tiene demasiado

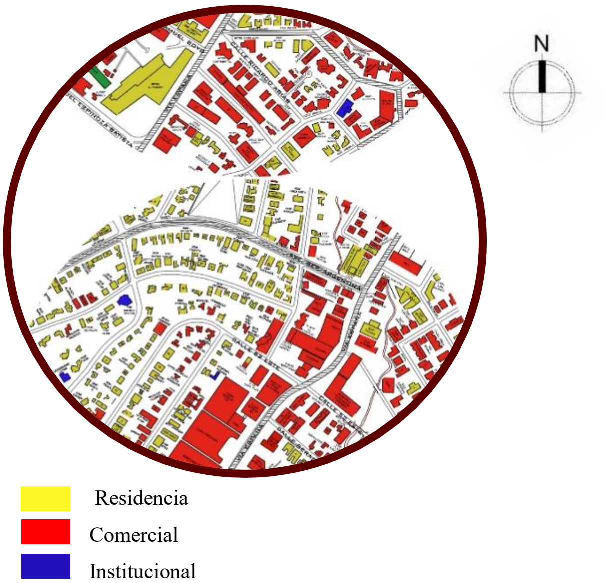

Figura 9: Mapa de uso de suelo

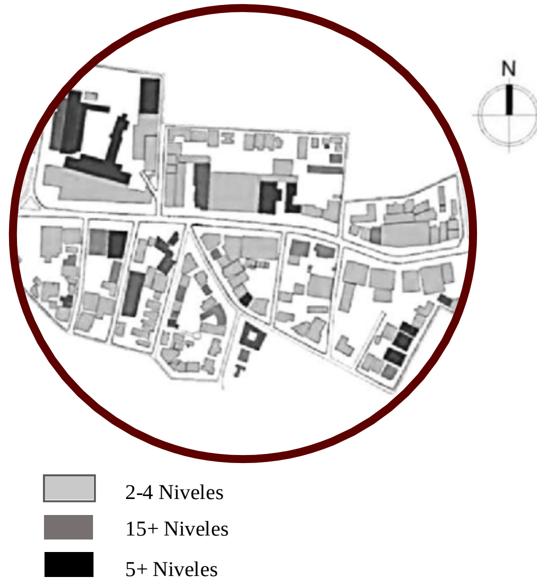

Figura 11: Estudio de Altimetría

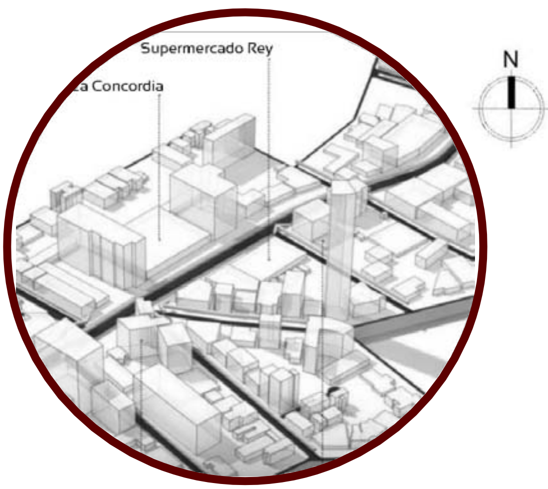

Figura 10: Mapa donde se observa la ubicación de zona de estudio en la Plaza Regency y Supermercado Rey

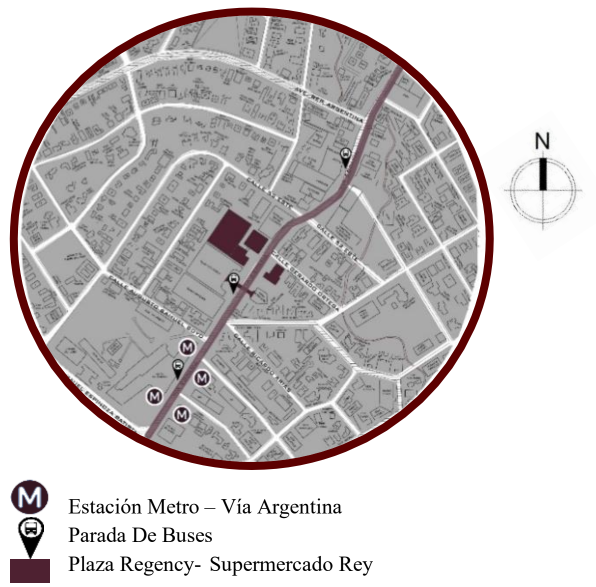

Figura 12: Mapa de movilidad y vialidad urbana

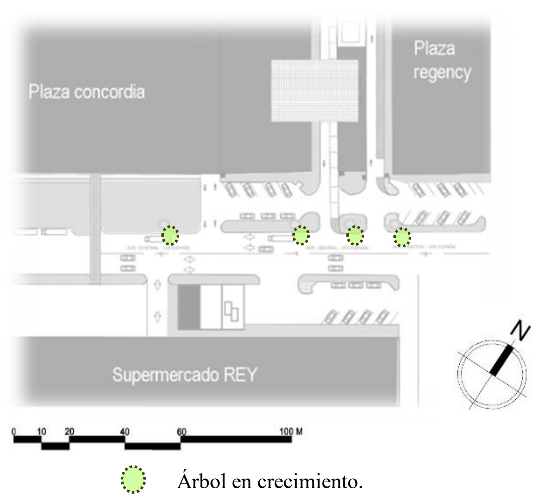

Figura 13: Mapa de espacios verdes o vegetación

IV. Discusión

Para desarrollar el estudio se confrontaron limitaciones y dificultades para obtener los permisos para posicionar las cámaras en el Rey y en Plaza Regency. Se sugiere continuar este estudio en un futuro. En esta investigación se incorporaron factores de análisis de sitio, los cuales se pueden seguir expandiendo y profundizando hasta el uso de un sistema de algoritmos, los cuales servirán para diagnosticar mejor las causas desde la morfología del lugar hasta el comportamiento al caminar. A futuro los cañones urbanos suelen ser un problema en las ciudades, pero los espacios de transición podrían mejorar la calidad del entorno urbano. Esa morfología, con espacio de transición, podría mejorar la comodidad térmica y el microclima del sitio y, en conjunto con los usos diversificados, aumentar la cantidad de peatones que pasan por el sector. Áreas con gran vitalidad, con espacios de transición en edificios, con uso comercial intenso y diversificado, tienen el potencial de verse rodeadas de peatones en busca de actividades comerciales o sencillamente pues se convierten en ejes atractivos y seguros de transito de un lugar a otro.

V. Conclusión

Este estudio de mapeo de peatones fue realizado en un sector de la Vía España, cuyo emplazamiento es concéntrico en la ciudad de Panamá, pues alberga una gran cantidad de flujo peatonal, actividad vehicular y diferentes tipos de usos comerciales y de servicio.

Los estudios se centran en la evaluación precisa y completa del entorno peatonal. Dichas mediciones pueden incluir las percepciones subjetivas de los peatones en este caso las sensaciones, intereses que ocurren en los espacios de transición y fuera del mismo.

Entre el cañón de Plaza Regency y el Supermercado Rey, comprobamos que la mayoría de las personas (entre 60% y 80% utilizan el espacio de transición de ambos edificios, porque posee características de seguridad, sombreamiento y presenta una alta intensidad comercial. Además, sirve como un punto de desplazamiento a diferentes zonas, que se encuentran adyacentes.

El Plan de revitalización del eje urbano de la Ciudad de Panamá, realizó un adoquinado de las aceras peatonales de la Vía España (cubriendo el perímetro externo de la Plaza Regency y el Supermercado Rey y las aceras paralelas a la Vía España), pero las mismas no son utilizadas por los peatones. Esto puede ser por que se encuentran expuestas a los rayos solares directos, no son atractivas y están próximas al flujo de autos. Aspectos estos que deben ser mejor estudiados futuramente.

Del total de personas que se contabilizaron en el sector de la Plaza Regency, el 60% de los peatones transitan por los espacios de transición del edificio, mientras que 25% pasa por la trasera de los automóviles, el 10% utiliza las aceras adoquinadas y el 5% cruza las cuatro vías de la Vía España. Estos números se relacionan con las desviaciones de ruta ya que un 25% opta por la ruta rápida, en cambio la mayoría de los peatones buscan los espacios de transición con sombra. En el sector del Supermercado Rey, la continuidad de su espacio permite que el 85% de los peatones utilicen con mayor intensidad esa ruta.

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- Lectures

- Printed material
- Graphic representations
- Computer programs
- Electronic material
- Any other original work

Authorship Policies

Global Journals follows the definition of authorship set up by the Open Association of Research Society, USA. According to its guidelines, authorship criteria must be based on:

1. Substantial contributions to the conception and acquisition of data, analysis, and interpretation of findings.
2. Drafting the paper and revising it critically regarding important academic content.
3. Final approval of the version of the paper to be published.

Changes in Authorship

The corresponding author should mention the name and complete details of all co-authors during submission and in manuscript. We support addition, rearrangement, manipulation, and deletions in authors list till the early view publication of the journal. We expect that corresponding author will notify all co-authors of submission. We follow COPE guidelines for changes in authorship.

Copyright

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Appealing Decisions

Unless specified in the notification, the Editorial Board's decision on publication of the paper is final and cannot be appealed before making the major change in the manuscript.

Acknowledgments

Contributors to the research other than authors credited should be mentioned in Acknowledgments. The source of funding for the research can be included. Suppliers of resources may be mentioned along with their addresses.

Declaration of funding sources

Global Journals is in partnership with various universities, laboratories, and other institutions worldwide in the research domain. Authors are requested to disclose their source of funding during every stage of their research, such as making analysis, performing laboratory operations, computing data, and using institutional resources, from writing an article to its submission. This will also help authors to get reimbursements by requesting an open access publication letter from Global Journals and submitting to the respective funding source.

Preparing your Manuscript

Authors can submit papers and articles in an acceptable file format: MS Word (doc, docx), LaTeX (.tex, .zip or .rar including all of your files), Adobe PDF (.pdf), rich text format (.rtf), simple text document (.txt), Open Document Text (.odt), and Apple Pages (.pages). Our professional layout editors will format the entire paper according to our official guidelines. This is one of the highlights of publishing with Global Journals—authors should not be concerned about the formatting of their paper. Global Journals accepts articles and manuscripts in every major language, be it Spanish, Chinese, Japanese, Portuguese, Russian, French, German, Dutch, Italian, Greek, or any other national language, but the title, subtitle, and abstract should be in English. This will facilitate indexing and the pre-peer review process.

The following is the official style and template developed for publication of a research paper. Authors are not required to follow this style during the submission of the paper. It is just for reference purposes.

Manuscript Style Instruction (Optional)

- Microsoft Word Document Setting Instructions.
- Font type of all text should be Swis721 Lt BT.
- Page size: 8.27" x 11'", left margin: 0.65, right margin: 0.65, bottom margin: 0.75.
- Paper title should be in one column of font size 24.
- Author name in font size of 11 in one column.
- Abstract: font size 9 with the word "Abstract" in bold italics.
- Main text: font size 10 with two justified columns.
- Two columns with equal column width of 3.38 and spacing of 0.2.
- First character must be three lines drop-capped.
- The paragraph before spacing of 1 pt and after of 0 pt.
- Line spacing of 1 pt.
- Large images must be in one column.
- The names of first main headings (Heading 1) must be in Roman font, capital letters, and font size of 10.
- The names of second main headings (Heading 2) must not include numbers and must be in italics with a font size of 10.

Structure and Format of Manuscript

The recommended size of an original research paper is under 15,000 words and review papers under 7,000 words. Research articles should be less than 10,000 words. Research papers are usually longer than review papers. Review papers are reports of significant research (typically less than 7,000 words, including tables, figures, and references)

A research paper must include:

a) A title which should be relevant to the theme of the paper.
b) A summary, known as an abstract (less than 150 words), containing the major results and conclusions.
c) Up to 10 keywords that precisely identify the paper's subject, purpose, and focus.
d) An introduction, giving fundamental background objectives.
e) Resources and techniques with sufficient complete experimental details (wherever possible by reference) to permit repetition, sources of information must be given, and numerical methods must be specified by reference.
f) Results which should be presented concisely by well-designed tables and figures.
g) Suitable statistical data should also be given.
h) All data must have been gathered with attention to numerical detail in the planning stage.

Design has been recognized to be essential to experiments for a considerable time, and the editor has decided that any paper that appears not to have adequate numerical treatments of the data will be returned unrefereed.

i) Discussion should cover implications and consequences and not just recapitulate the results; conclusions should also be summarized.
j) There should be brief acknowledgments.
k) There ought to be references in the conventional format. Global Journals recommends APA format.

Authors should carefully consider the preparation of papers to ensure that they communicate effectively. Papers are much more likely to be accepted if they are carefully designed and laid out, contain few or no errors, are summarizing, and follow instructions. They will also be published with much fewer delays than those that require much technical and editorial correction.

The Editorial Board reserves the right to make literary corrections and suggestions to improve brevity.

Format Structure

It is necessary that authors take care in submitting a manuscript that is written in simple language and adheres to published guidelines.

All manuscripts submitted to Global Journals should include:

Title

The title page must carry an informative title that reflects the content, a running title (less than 45 characters together with spaces), names of the authors and co-authors, and the place(s) where the work was carried out.

Author details

The full postal address of any related author(s) must be specified.

Abstract

The abstract is the foundation of the research paper. It should be clear and concise and must contain the objective of the paper and inferences drawn. It is advised to not include big mathematical equations or complicated jargon.

Many researchers searching for information online will use search engines such as Google, Yahoo or others. By optimizing your paper for search engines, you will amplify the chance of someone finding it. In turn, this will make it more likely to be viewed and cited in further works. Global Journals has compiled these guidelines to facilitate you to maximize the web-friendliness of the most public part of your paper.

Keywords

A major lynchpin of research work for the writing of research papers is the keyword search, which one will employ to find both library and internet resources. Up to eleven keywords or very brief phrases have to be given to help data retrieval, mining, and indexing.

One must be persistent and creative in using keywords. An effective keyword search requires a strategy: planning of a list of possible keywords and phrases to try.

Choice of the main keywords is the first tool of writing a research paper. Research paper writing is an art. Keyword search should be as strategic as possible.

One should start brainstorming lists of potential keywords before even beginning searching. Think about the most important concepts related to research work. Ask, "What words would a source have to include to be truly valuable in a research paper?" Then consider synonyms for the important words.

It may take the discovery of only one important paper to steer in the right keyword direction because, in most databases, the keywords under which a research paper is abstracted are listed with the paper.

Numerical Methods

Numerical methods used should be transparent and, where appropriate, supported by references.

Abbreviations

Authors must list all the abbreviations used in the paper at the end of the paper or in a separate table before using them.

Formulas and equations

Authors are advised to submit any mathematical equation using either MathJax, KaTeX, or LaTeX, or in a very high-quality image.

Tables, Figures, and Figure Legends

Tables: Tables should be cautiously designed, uncrowned, and include only essential data. Each must have an Arabic number, e.g., Table 4, a self-explanatory caption, and be on a separate sheet. Authors must submit tables in an editable format and not as images. References to these tables (if any) must be mentioned accurately.

Figures

Figures are supposed to be submitted as separate files. Always include a citation in the text for each figure using Arabic numbers, e.g., Fig. 4. Artwork must be submitted online in vector electronic form or by emailing it.

Preparation of Eletronic Figures for Publication

Although low-quality images are sufficient for review purposes, print publication requires high-quality images to prevent the final product being blurred or fuzzy. Submit (possibly by e-mail) EPS (line art) or TIFF (halftone/ photographs) files only. MS PowerPoint and Word Graphics are unsuitable for printed pictures. Avoid using pixel-oriented software. Scans (TIFF only) should have a resolution of at least 350 dpi (halftone) or 700 to 1100 dpi (line drawings). Please give the data for figures in black and white or submit a Color Work Agreement form. EPS files must be saved with fonts embedded (and with a TIFF preview, if possible).

For scanned images, the scanning resolution at final image size ought to be as follows to ensure good reproduction: line art: >650 dpi; halftones (including gel photographs): >350 dpi; figures containing both halftone and line images: >650 dpi.

Color charges: Authors are advised to pay the full cost for the reproduction of their color artwork. Hence, please note that if there is color artwork in your manuscript when it is accepted for publication, we would require you to complete and return a Color Work Agreement form before your paper can be published. Also, you can email your editor to remove the color fee after acceptance of the paper.

Tips for Writing a Good Quality Engineering Research Paper

Techniques for writing a good quality engineering research paper:

1. Choosing the topic: In most cases, the topic is selected by the interests of the author, but it can also be suggested by the guides. You can have several topics, and then judge which you are most comfortable with. This may be done by asking several questions of yourself, like "Will I be able to carry out a search in this area? Will I find all necessary resources to accomplish the search? Will I be able to find all information in this field area?" If the answer to this type of question is "yes," then you ought to choose that topic. In most cases, you may have to conduct surveys and visit several places. Also, you might have to do a lot of work to find all the rises and falls of the various data on that subject. Sometimes, detailed information plays a vital role, instead of short information. Evaluators are human: The first thing to remember is that evaluators are also human beings. They are not only meant for rejecting a paper. They are here to evaluate your paper. So present your best aspect.

2. Think like evaluators: If you are in confusion or getting demotivated because your paper may not be accepted by the evaluators, then think, and try to evaluate your paper like an evaluator. Try to understand what an evaluator wants in your research paper, and you will automatically have your answer. Make blueprints of paper: The outline is the plan or framework that will help you to arrange your thoughts. It will make your paper logical. But remember that all points of your outline must be related to the topic you have chosen.

3. Ask your guides: If you are having any difficulty with your research, then do not hesitate to share your difficulty with your guide (if you have one). They will surely help you out and resolve your doubts. If you can't clarify what exactly you require for your work, then ask your supervisor to help you with an alternative. He or she might also provide you with a list of essential readings.

4. Use of computer is recommended: As you are doing research in the field of research engineering then this point is quite obvious. Use right software: Always use good quality software packages. If you are not capable of judging good software, then you can lose the quality of your paper unknowingly. There are various programs available to help you which you can get through the internet.

5. Use the internet for help: An excellent start for your paper is using Google. It is a wondrous search engine, where you can have your doubts resolved. You may also read some answers for the frequent question of how to write your research paper or find a model research paper. You can download books from the internet. If you have all the required books, place importance on reading, selecting, and analyzing the specified information. Then sketch out your research paper. Use big pictures: You may use encyclopedias like Wikipedia to get pictures with the best resolution. At Global Journals, you should strictly follow here.

6. Bookmarks are useful: When you read any book or magazine, you generally use bookmarks, right? It is a good habit which helps to not lose your continuity. You should always use bookmarks while searching on the internet also, which will make your search easier.

7. Revise what you wrote: When you write anything, always read it, summarize it, and then finalize it.

8. Make every effort: Make every effort to mention what you are going to write in your paper. That means always have a good start. Try to mention everything in the introduction—what is the need for a particular research paper. Polish your work with good writing skills and always give an evaluator what he wants. Make backups: When you are going to do any important thing like making a research paper, you should always have backup copies of it either on your computer or on paper. This protects you from losing any portion of your important data.

9. Produce good diagrams of your own: Always try to include good charts or diagrams in your paper to improve quality. Using several unnecessary diagrams will degrade the quality of your paper by creating a hodgepodge. So always try to include diagrams which were made by you to improve the readability of your paper. Use of direct quotes: When you do research relevant to literature, history, or current affairs, then use of quotes becomes essential, but if the study is relevant to science, use of quotes is not preferable.

10. Use proper verb tense: Use proper verb tenses in your paper. Use past tense to present those events that have happened. Use present tense to indicate events that are going on. Use future tense to indicate events that will happen in the future. Use of wrong tenses will confuse the evaluator. Avoid sentences that are incomplete.

11. Pick a good study spot: Always try to pick a spot for your research which is quiet. Not every spot is good for studying.

12. Know what you know: Always try to know what you know by making objectives, otherwise you will be confused and unable to achieve your target.

13. Use good grammar: Always use good grammar and words that will have a positive impact on the evaluator; use of good vocabulary does not mean using tough words which the evaluator has to find in a dictionary. Do not fragment sentences. Eliminate one-word sentences. Do not ever use a big word when a smaller one would suffice.

Verbs have to be in agreement with their subjects. In a research paper, do not start sentences with conjunctions or finish them with prepositions. When writing formally, it is advisable to never split an infinitive because someone will (wrongly) complain. Avoid clichés like a disease. Always shun irritating alliteration. Use language which is simple and straightforward. Put together a neat summary.

14. Arrangement of information: Each section of the main body should start with an opening sentence, and there should be a changeover at the end of the section. Give only valid and powerful arguments for your topic. You may also maintain your arguments with records.

15. Never start at the last minute: Always allow enough time for research work. Leaving everything to the last minute will degrade your paper and spoil your work.

16. Multitasking in research is not good: Doing several things at the same time is a bad habit in the case of research activity. Research is an area where everything has a particular time slot. Divide your research work into parts, and do a particular part in a particular time slot.

17. Never copy others' work: Never copy others' work and give it your name because if the evaluator has seen it anywhere, you will be in trouble. Take proper rest and food: No matter how many hours you spend on your research activity, if you are not taking care of your health, then all your efforts will have been in vain. For quality research, take proper rest and food.

18. Go to seminars: Attend seminars if the topic is relevant to your research area. Utilize all your resources.

19. Refresh your mind after intervals: Try to give your mind a rest by listening to soft music or sleeping in intervals. This will also improve your memory. Acquire colleagues: Always try to acquire colleagues. No matter how sharp you are, if you acquire colleagues, they can give you ideas which will be helpful to your research.

20. Think technically: Always think technically. If anything happens, search for its reasons, benefits, and demerits. Think and then print: When you go to print your paper, check that tables are not split, headings are not detached from their descriptions, and page sequence is maintained.

21. Adding unnecessary information: Do not add unnecessary information like "I have used MS Excel to draw graphs." Irrelevant and inappropriate material is superfluous. Foreign terminology and phrases are not apropos. One should never take a broad view. Analogy is like feathers on a snake. Use words properly, regardless of how others use them. Remove quotations. Puns are for kids, not grunt readers. Never oversimplify: When adding material to your research paper, never go for oversimplification; this will definitely irritate the evaluator. Be specific. Never use rhythmic redundancies. Contractions shouldn't be used in a research paper. Comparisons are as terrible as clichés. Give up ampersands, abbreviations, and so on. Remove commas that are not necessary. Parenthetical words should be between brackets or commas. Understatement is always the best way to put forward earth-shaking thoughts. Give a detailed literary review.
22. Report concluded results: Use concluded results. From raw data, filter the results, and then conclude your studies based on measurements and observations taken. An appropriate number of decimal places should be used. Parenthetical remarks are prohibited here. Proofread carefully at the final stage. At the end, give an outline to your arguments. Spot perspectives of further study of the subject. Justify your conclusion at the bottom sufficiently, which will probably include examples.
23. Upon conclusion: Once you have concluded your research, the next most important step is to present your findings. Presentation is extremely important as it is the definite medium though which your research is going to be in print for the rest of the crowd. Care should be taken to categorize your thoughts well and present them in a logical and neat manner. A good quality research paper format is essential because it serves to highlight your research paper and bring to light all necessary aspects of your research.

Informal Guidelines of Research Paper Writing

Key points to remember:

- Submit all work in its final form.
- Write your paper in the form which is presented in the guidelines using the template.
- Please note the criteria peer reviewers will use for grading the final paper.

Final points:

One purpose of organizing a research paper is to let people interpret your efforts selectively. The journal requires the following sections, submitted in the order listed, with each section starting on a new page:

The introduction: This will be compiled from reference matter and reflect the design processes or outline of basis that directed you to make a study. As you carry out the process of study, the method and process section will be constructed like that. The results segment will show related statistics in nearly sequential order and direct reviewers to similar intellectual paths throughout the data that you gathered to carry out your study.

The discussion section:

This will provide understanding of the data and projections as to the implications of the results. The use of good quality references throughout the paper will give the effort trustworthiness by representing an alertness to prior workings.

Writing a research paper is not an easy job, no matter how trouble-free the actual research or concept. Practice, excellent preparation, and controlled record-keeping are the only means to make straightforward progression.

General style:

Specific editorial column necessities for compliance of a manuscript will always take over from directions in these general guidelines.

To make a paper clear: Adhere to recommended page limits.

Mistakes to avoid:

- Insertion of a title at the foot of a page with subsequent text on the next page.
- Separating a table, chart, or figure—confine each to a single page.
- Submitting a manuscript with pages out of sequence.
- In every section of your document, use standard writing style, including articles ("a" and "the").
- Keep paying attention to the topic of the paper.

- Use paragraphs to split each significant point (excluding the abstract).
- Align the primary line of each section.
- Present your points in sound order.
- Use present tense to report well-accepted matters.
- Use past tense to describe specific results.
- Do not use familiar wording; don't address the reviewer directly. Don't use slang or superlatives.
- Avoid use of extra pictures—include only those figures essential to presenting results.

Title page:

Choose a revealing title. It should be short and include the name(s) and address(es) of all authors. It should not have acronyms or abbreviations or exceed two printed lines.

Abstract: This summary should be two hundred words or less. It should clearly and briefly explain the key findings reported in the manuscript and must have precise statistics. It should not have acronyms or abbreviations. It should be logical in itself. Do not cite references at this point.

An abstract is a brief, distinct paragraph summary of finished work or work in development. In a minute or less, a reviewer can be taught the foundation behind the study, common approaches to the problem, relevant results, and significant conclusions or new questions.

Write your summary when your paper is completed because how can you write the summary of anything which is not yet written? Wealth of terminology is very essential in abstract. Use comprehensive sentences, and do not sacrifice readability for brevity; you can maintain it succinctly by phrasing sentences so that they provide more than a lone rationale. The author can at this moment go straight to shortening the outcome. Sum up the study with the subsequent elements in any summary. Try to limit the initial two items to no more than one line each.

Reason for writing the article—theory, overall issue, purpose.

- Fundamental goal.
- To-the-point depiction of the research.
- Consequences, including definite statistics—if the consequences are quantitative in nature, account for this; results of any numerical analysis should be reported. Significant conclusions or questions that emerge from the research.

Approach:

- o Single section and succinct.
- o An outline of the job done is always written in past tense.
- o Concentrate on shortening results—limit background information to a verdict or two.
- o Exact spelling, clarity of sentences and phrases, and appropriate reporting of quantities (proper units, important statistics) are just as significant in an abstract as they are anywhere else.

Introduction:

The introduction should "introduce" the manuscript. The reviewer should be presented with sufficient background information to be capable of comprehending and calculating the purpose of your study without having to refer to other works. The basis for the study should be offered. Give the most important references, but avoid making a comprehensive appraisal of the topic. Describe the problem visibly. If the problem is not acknowledged in a logical, reasonable way, the reviewer will give no attention to your results. Speak in common terms about techniques used to explain the problem, if needed, but do not present any particulars about the protocols here.

The following approach can create a valuable beginning:

- o Explain the value (significance) of the study.
- o Defend the model—why did you employ this particular system or method? What is its compensation? Remark upon its appropriateness from an abstract point of view as well as pointing out sensible reasons for using it.
- o Present a justification. State your particular theory(-ies) or aim(s), and describe the logic that led you to choose them.
- o Briefly explain the study's tentative purpose and how it meets the declared objectives.

Approach:

Use past tense except for when referring to recognized facts. After all, the manuscript will be submitted after the entire job is done. Sort out your thoughts; manufacture one key point for every section. If you make the four points listed above, you will need at least four paragraphs. Present surrounding information only when it is necessary to support a situation. The reviewer does not desire to read everything you know about a topic. Shape the theory specifically—do not take a broad view.

As always, give awareness to spelling, simplicity, and correctness of sentences and phrases.

Procedures (methods and materials):

This part is supposed to be the easiest to carve if you have good skills. A soundly written procedures segment allows a capable scientist to replicate your results. Present precise information about your supplies. The suppliers and clarity of reagents can be helpful bits of information. Present methods in sequential order, but linked methodologies can be grouped as a segment. Be concise when relating the protocols. Attempt to give the least amount of information that would permit another capable scientist to replicate your outcome, but be cautious that vital information is integrated. The use of subheadings is suggested and ought to be synchronized with the results section.

When a technique is used that has been well-described in another section, mention the specific item describing the way, but draw the basic principle while stating the situation. The purpose is to show all particular resources and broad procedures so that another person may use some or all of the methods in one more study or referee the scientific value of your work. It is not to be a step-by-step report of the whole thing you did, nor is a methods section a set of orders.

Materials:

Materials may be reported in part of a section or else they may be recognized along with your measures.

Methods:

- Report the method and not the particulars of each process that engaged the same methodology.
- Describe the method entirely.
- To be succinct, present methods under headings dedicated to specific dealings or groups of measures.
- Simplify—detail how procedures were completed, not how they were performed on a particular day.
- If well-known procedures were used, account for the procedure by name, possibly with a reference, and that's all.

Approach:

It is embarrassing to use vigorous voice when documenting methods without using first person, which would focus the reviewer's interest on the researcher rather than the job. As a result, when writing up the methods, most authors use third person passive voice.

Use standard style in this and every other part of the paper—avoid familiar lists, and use full sentences.

What to keep away from:

- Resources and methods are not a set of information.
- Skip all descriptive information and surroundings—save it for the argument.
- Leave out information that is immaterial to a third party.

Results:

The principle of a results segment is to present and demonstrate your conclusion. Create this part as entirely objective details of the outcome, and save all understanding for the discussion.

The page length of this segment is set by the sum and types of data to be reported. Use statistics and tables, if suitable, to present consequences most efficiently.

You must clearly differentiate material which would usually be incorporated in a study editorial from any unprocessed data or additional appendix matter that would not be available. In fact, such matters should not be submitted at all except if requested by the instructor.

Content:

- Sum up your conclusions in text and demonstrate them, if suitable, with figures and tables.
- In the manuscript, explain each of your consequences, and point the reader to remarks that are most appropriate.
- Present a background, such as by describing the question that was addressed by creation of an exacting study.
- Explain results of control experiments and give remarks that are not accessible in a prescribed figure or table, if appropriate.
- Examine your data, then prepare the analyzed (transformed) data in the form of a figure (graph), table, or manuscript.

What to stay away from:

- Do not discuss or infer your outcome, report surrounding information, or try to explain anything.
- Do not include raw data or intermediate calculations in a research manuscript.
- Do not present similar data more than once.
- A manuscript should complement any figures or tables, not duplicate information.
- Never confuse figures with tables—there is a difference.

Approach:

As always, use past tense when you submit your results, and put the whole thing in a reasonable order.

Put figures and tables, appropriately numbered, in order at the end of the report.

If you desire, you may place your figures and tables properly within the text of your results section.

Figures and tables:

If you put figures and tables at the end of some details, make certain that they are visibly distinguished from any attached appendix materials, such as raw facts. Whatever the position, each table must be titled, numbered one after the other, and include a heading. All figures and tables must be divided from the text.

Discussion:

The discussion is expected to be the trickiest segment to write. A lot of papers submitted to the journal are discarded based on problems with the discussion. There is no rule for how long an argument should be.

Position your understanding of the outcome visibly to lead the reviewer through your conclusions, and then finish the paper with a summing up of the implications of the study. The purpose here is to offer an understanding of your results and support all of your conclusions, using facts from your research and generally accepted information, if suitable. The implication of results should be fully described.

Infer your data in the conversation in suitable depth. This means that when you clarify an observable fact, you must explain mechanisms that may account for the observation. If your results vary from your prospect, make clear why that may have happened. If your results agree, then explain the theory that the proof supported. It is never suitable to just state that the data approved the prospect, and let it drop at that. Make a decision as to whether each premise is supported or discarded or if you cannot make a conclusion with assurance. Do not just dismiss a study or part of a study as "uncertain."

Research papers are not acknowledged if the work is imperfect. Draw what conclusions you can based upon the results that you have, and take care of the study as a finished work.

- You may propose future guidelines, such as how an experiment might be personalized to accomplish a new idea.
- Give details of all of your remarks as much as possible, focusing on mechanisms.
- Make a decision as to whether the tentative design sufficiently addressed the theory and whether or not it was correctly restricted. Try to present substitute explanations if they are sensible alternatives.
- One piece of research will not counter an overall question, so maintain the large picture in mind. Where do you go next? The best studies unlock new avenues of study. What questions remain?
- Recommendations for detailed papers will offer supplementary suggestions.

Approach:

When you refer to information, differentiate data generated by your own studies from other available information. Present work done by specific persons (including you) in past tense.

Describe generally acknowledged facts and main beliefs in present tense.

The Administration Rules

Administration Rules to Be Strictly Followed before Submitting Your Research Paper to Global Journals Inc.

Please read the following rules and regulations carefully before submitting your research paper to Global Journals Inc. to avoid rejection.

Segment draft and final research paper: You have to strictly follow the template of a research paper, failing which your paper may get rejected. You are expected to write each part of the paper wholly on your own. The peer reviewers need to identify your own perspective of the concepts in your own terms. Please do not extract straight from any other source, and do not rephrase someone else's analysis. Do not allow anyone else to proofread your manuscript.

Written material: You may discuss this with your guides and key sources. Do not copy anyone else's paper, even if this is only imitation, otherwise it will be rejected on the grounds of plagiarism, which is illegal. Various methods to avoid plagiarism are strictly applied by us to every paper, and, if found guilty, you may be blacklisted, which could affect your career adversely. To guard yourself and others from possible illegal use, please do not permit anyone to use or even read your paper and file.

Criterion for Grading a Research Paper (Compilation) by Global Journals

Please note that following table is only a Grading of "Paper Compilation" and not on "Performed/Stated Research" whose grading solely depends on Individual Assigned Peer Reviewer and Editorial Board Member. These can be available only on request and after decision of Paper. This report will be the property of Global Journals.

Topics	Grades		
	A-B	**C-D**	**E-F**
Abstract	Clear and concise with appropriate content, Correct format. 200 words or below	Unclear summary and no specific data, Incorrect form Above 200 words	No specific data with ambiguous information Above 250 words
Introduction	Containing all background details with clear goal and appropriate details, flow specification, no grammar and spelling mistake, well organized sentence and paragraph, reference cited	Unclear and confusing data, appropriate format, grammar and spelling errors with unorganized matter	Out of place depth and content, hazy format
Methods and Procedures	Clear and to the point with well arranged paragraph, precision and accuracy of facts and figures, well organized subheads	Difficult to comprehend with embarrassed text, too much explanation but completed	Incorrect and unorganized structure with hazy meaning
Result	Well organized, Clear and specific, Correct units with precision, correct data, well structuring of paragraph, no grammar and spelling mistake	Complete and embarrassed text, difficult to comprehend	Irregular format with wrong facts and figures
Discussion	Well organized, meaningful specification, sound conclusion, logical and concise explanation, highly structured paragraph reference cited	Wordy, unclear conclusion, spurious	Conclusion is not cited, unorganized, difficult to comprehend
References	Complete and correct format, well organized	Beside the point, Incomplete	Wrong format and structuring

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