Thermo-finance: the link between financial engineering and financial stability

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Abstract: Schinckus (2010) defines econophysics as a new approach which applies physics concepts to understand economic and financial phenomena; this paper belongs to the school of econophysics. The goal of this paper is to apply the three principles of thermodynamics into the field of finance. The qualitative results obtained are the three principles of financial engineering which describe the evolution, the dispersion, and the measure of risk inside the financial system. We push further the reasoning to describe the three axiomatic laws of finance which put the three principles observed into motion. Finally, we describe the three financial engineering construction rules that have to be respected, in order to create financial engineering products and solutions that are sustainable over time, thereby enhancing systemic financial stability.

Keywords: Econophysics; Financial stability; Axiomatic laws of finance; Principles of financial engineering; Construction rules of financial engineering
1. Introduction

According to the U.S. Department of Labor (2008) engineering is an approach that leads to creating solutions adapted to given problems. The creation of a solution covers several stages, which range from the theoretical conception to the practical implementation, and finally the monitoring of the designed solution. The concept of solution is also very broad. In fact, the solution designed by an engineer can be a machine, an instrument, a process, a material, a system, an algorithm, an organization, a building, a mean of transport, etc. Engineering is the approach that allows the combination of human intellect with the forces of nature, to solve a problem or to optimize an existing solution.

Gilbert (1991) defines science as the study of natural phenomena in order to understand the laws which put them into motion, then model them in order to gain some forecasting capability. Engineering is the bridge between the basic sciences that aim to understand, and the applied sciences that aim to use the laws of nature to design solutions. To achieve this, any branch of engineering is based on a scientific corpus, which includes not only a theoretical corpus, but also empirical results.

This classic distinction between science and engineering is sometimes outdated in reality. It happens that engineers, who work on a specific area, are faced with an insufficient scientific corpus. Engineers will then embark on a process of research and development on this niche, and turn into real researchers. Through their engineering process, they help to develop the underlying scientific corpus. This process is defined as engineering research by the National Academy of Engineering (1995).

Over time, the corpus of scientific knowledge has expanded, leading to the creation of new engineering fields. The corpus of economic, human and social sciences was also enriched, leading to discussions about the fact, if these social fields were sciences or not? By this we mean, are they sciences quite comparable to the natural sciences such as physics and chemistry for example? A science is defined by the study of natural forces reproducible anywhere and at any time. These eternal natural forces are the engines of physicochemical mechanisms. In the same way, are economics governed by rational mechanisms constantly in motion, which lead to a reproducibility of results? If so, then this is a natural science. Hicks (1984) conclude by stating that economics is on the edge of science and the edge of history.
Traditional engineering consisted in creating a bridge between so-called natural sciences (physics, chemistry, biology, etc.) and concrete applications that offer solutions. In recent decades, as new fields of sciences have emerged, new engineering fields also emerged, resulting in the same discussion than before. These pioneering branches of engineering aim to take root in economics, human and social sciences, in order to conceive concrete solutions. The debate that once existed in the past about the relevance of qualifying certain branches of knowledge such as economics as scientific or not, has been transposed to the field of engineering. Can we qualify as engineering, an intellectual approach that consists in solving problems based on a corpus of economics, human or social sciences? Financial engineering is one of these pioneering engineering fields. In its Occupational Outlook Handbook, the U.S. Department of Labor (2008) still does not cover these pioneering engineering disciplines, although Ivy League Universities such as the Columbia University, started offering degree programs in financial engineering for example. These new fields of engineering aim to follow an intellectual research methodology comparable to the ones used in classical engineering, based on theoretical study of the laws in motion, mathematical modelling of the principles, and the accumulation of robust empirical results.

Financial engineering is a relatively young discipline as compared to the long history of finance. Today, financial engineering rests on a solid body of theoretical knowledge: the theory of efficient markets which aims to understand how markets react throughout time, the theory of capital structure which aims to define an optimal capital structure for firms, the theory of modern portfolio management which aims to propose an optimal asset allocation, the theory of financials assets which focuses on the fair valuation of financial securities, the theory of options evaluation, and the theory of behavioral finance which aims to adjust the hypothesis of rational economic man to the real world constraints. Taken together, a financier has the theoretical tools to decide how to perform the main tasks of his function: how to allocate his capital – be it on a portfolio or inside a company – how to price the financial securities he wants to implement, and how to make some level of market predictions.

We would like to introduce financial engineering through a quote from Theodore Von Karman: science studies the world as it is, while engineering builds a world that has never existed. The financial engineering approach is like all other fields of engineering: a matter of innovation. The very reason for the existence of financial engineering is not to settle for conventional financial
securities and standard financial schemes, but rather to build new solutions that meet the needs of the client, through a real work of art and innovation. A financier presents his clients the world as it is; a financial engineer builds for his clients the world they desire. But here is where the theoretical corpus proves insufficient: no rules have been enunciated before, through a holistic approach, to define what makes a financial engineering construction sustainable over time. Just like the work of a civil engineer whose building will collapse if the laws of gravity are not respected, the work of financial engineers can collapse just as quickly, if some fundamental laws are omitted. We will argue that if financial engineering innovations are made sustainable, crises situations will be avoided, thereby increasing systemic financial stability.

The rest of this paper is organized as follow: Section 2 describes the research methodology. Section 3 describes the three principles observed in financial engineering which are deducted from an analogy with the principles of thermodynamics. Section 4 sheds light on the three axiomatic laws of finance which put the principles observed into motion. Section 5 explains construction rules that have to be followed by financial engineers in order to respect the principles and build solutions which are sustainable; finally Section 6 presents concluding remarks.

2. Methodology

According to Krebs (2008), there is a fundamental difference in science between laws and principles. The principles represent observations that materialize continuously without any explanation of the mechanism that leads to their realization. The mechanism in question is described by the laws; it is the laws which explain why the principles actually work. For example, Newton’s apple falls once dropped, this is a principle of evolution. Why does she fall? Because the force of gravity pulls it downward, this is the fundamental law that explains the principle of evolution observed.

This distinction between laws and principles will define the research methodology we will follow in this paper:

- In Section 3, we will follow a descriptive research methodology. We will apply the three principles of thermodynamics to finance, to infer the three principles of financial engineering. We will show how any financial engineering work which does not respect these principles lead to a disequilibrium situation, which threatens the solution designed.
In Section 4, we will follow an explanatory research methodology to explain why these principles actually work. We will make three hypotheses about axiomatic laws in the field of finance, which put capital into motion, and make the principles a reality.

In Section 5, we will follow a predictive research methodology. We will infer three construction rules for financial engineering products and solutions, which have to be respected in order to generate a sustainable financial construction, thereby decreasing the risk of a crisis, and enhancing systemic financial stability. This predictive research part is essentially qualitative, and requires further quantitative research in the future to produce empirical back testing results.

Fig. 1. Dynamics of laws, principles, and rules in financial engineering

3. The three observable principles in financial engineering

3.1 Principle no. 1: The principle of conservation

Schinckus (2010) defines econophysics as a new approach which applies physics concepts to understand economic and financial phenomena; this paper belongs to the school of econophysics. Thermodynamics is the science that studies the dynamics - that is the movements or transfers - of heat, according to the definition of Klein and Nellis (2012). In thermodynamics, state variables are defined to characterize a system. Temperature, pressure, and volume are some examples of possible state variables. These state variables can even be combined to form a state function, such as the internal energy of a system. In financial engineering, we propose to consider as a major state variable, not the return of financial securities, but rather the risk of financial securities. It is around this state variable of risk, which is specific to each financial instrument, that we will build our proposition.

According to Klein and Nellis (2012) the first principle of thermodynamics states that when an open system undergoes a given transformation, the internal energy is conserved. Indeed, if the internal
energy of the system drops, it means that the internal energy of the external universe has increased. There has been a transfer of this internal energy in the form of heat or mechanical work between the system and the universe. This principle of conservation of internal energy is part of a long tradition in physics, which are the equations of conservation. These conservation laws are found in several scientific fields: mechanics, energy, electricity, chemistry, etc., and are illustrated by the chemist Antoine Lavoisier quote Nothing is lost, nothing is created, everything is transformed.

We transpose this preservation principle into financial engineering. If we consider that a financial security is characterized by a given state variable which is its risk, then we argue that any financial engineering technique will not modify the overall quantity of risk. The only contribution of financial engineering is to allow a transfer of risk, between the isolated system and the external universe that surrounds it. If the risk of the system falls, it implies that it is actually transferred out of the system into the universe, and that the risk as a whole remains a constant. This principle is illustrated in Figure 2.

![Fig. 2. A general illustration of the conservation principle](image)

Financial engineering is therefore a set of techniques whose purpose is to reallocate risk within the financial system. This can be demonstrated using a descriptive approach of the different financial engineering operations. In order to be exhaustive in our descriptive approach, we will use in this paper a broad definition of the term financial engineering, one which is close to financial innovation. We will include in the financial engineering operations, not only the financial markets techniques, like issuing derivatives or issuing structured products thanks to quantitative methods, but we will also include the corporate finance operations, like issuing vanilla securities in equity capital markets or debt capital markets. As illustrated in the Figure 3:

1. Performing an Initial Public Offering (IPO) is equivalent to a risk transfer to the minority shareholders
2. A Debt Capital issue is equivalent to a risk transfer to bond holders and note holders

3. An Asset Securitization is equivalent to a risk transfer to investors exposed to the assets through a special purpose vehicle (SPV)

4. A Factoring of Receivables is equivalent to a risk transfer to the factoring company, which can be with or without recourse against the parent company

5. A Hedging Operation through the issue of Derivatives is equivalent to the a risk transfer to the derivative counterparty

6. A Structured Product Issue is equivalent to a risk transfer to the issuer of the structured securities

7. An Insurance Policy is equivalent to a risk transfer to the insurance company and to all the other members of the insurance scheme

From this descriptive illustration, we can grasp the general principle of risk conservation: the techniques of financial engineering do not diminish the total quantity of risk, these techniques enable a reallocation of risk between various stakeholders inside the financial system.

**Fig. 3.** A detailed illustration of the conservation principle

**3.2 Principle no. 2: The principle of evolution**
We have seen that in thermodynamics, several state variables can be combined to form a state function, such as internal energy. Another very important state function, which is at the heart of the second principle, is called entropy. Entropy is a thermodynamic notion that has been observed for a long time, but it was only really understood with the work of Ludwig Boltzmann who analyzed entropy from a microscopic point of view. Boltzmann developed the kinetic theory of gases which explains how the particles composing a system such as a gas move at the microscopic level, while at the macroscopic level the system seems to be at rest. According to Klein and Nellis (2012) entropy represents the disorder of particles at the microscopic level. More precisely, it represents the number of possible states in which one can arrange the different particles composing the system. Let's take an example, suppose we have a set of 4 identical cards, which will be spread over 4 slots from A to D. Each slot can accommodate multiple cards, not just one. If we decide to impose a constraint that is to fix 3 cards on the first slot, the last card can be placed on one of the four slots. This means that there are four ways to organize these cards. Given the constraint we have imposed on the system, the degree of freedom really depends only on the location of the last card. The entropy of the system depends on the number of possible states in which it can be stored. Here in this case, the number of states is low, so the entropy will be low. If we remove the initial constraint, it means that the degree of freedom resides in all the map. The number of states in which the system components can be stored at the microscopic level becomes higher than in the first experience, which means that the disorder and entropy of the system have increased. From a macroscopic point of view, the two cases are identical, since the system seems to consist of four cards in the first and second experience.

Entropy is therefore a measure of the disorder inside a system, which increases when the number of possible states (that is, the number of ways to store the particles in the system) increases. The first principle of thermodynamics tells us that internal energy is conserved, but it does not indicate the direction of evolution. Suppose the temperature of a system is high and the temperature of the universe is cold, nothing in the first principle indicates the direction of evolution. Is it the system that will warm up more and the outside world that will cool down? Or the opposite, is it the system that will cool down to warm up the universe? The second principle answers this question; that is why it is called a principle of evolution: it’s because it defines a direction of evolution for the system in order to reach a new equilibrium. As stated by Klein and Nellis (2012) the second principle states that a system left free (that is to say without constraint) evolves in the direction which maximizes its entropy. It is by maximizing his entropy that he gets closer to equilibrium.
In the case of the card game, if the storage experience is purely random, that is to say it is not subject to any constraints, the system will find its equilibrium by maximizing its entropy. In other words, it is much more likely to arrive at a situation where the cards are spread over many boxes, rather than arriving at an orderly situation where they are all fixed on the first slot. The system will evolve in the direction which maximizes its entropy, in order to reach equilibrium.

In the case of the heat transfer mentioned above, in which direction will the system evolve? It turns out that heat comes from an agitation of particles. The more they vibrate the higher their temperature, and the higher the entropy, that is to say the disorder of the system increases. We therefore have the choice between two situations:

1. If the system that is already hot, warms up even more and the cold universe gets colder, it means that the agitation of the particles in the system increases and that of the universe decreases, which implies a decrease of global entropy.

2. If the warm system cools and the cold universe heats up, it means that the agitation of the particles in the system is decreasing and that of the universe is progressing further, which implies an overall increase of entropy.

The system will evolve in the second direction, because it is the one which maximizes the global entropy. The warm body will cool down and the cold body will absorb its heat. The principle of evolution makes it possible to predict the direction of movement.

What about financial engineering? First, it should be noted that the entropy increases in thermodynamics only when the transformation is irreversible. It means that once the system goes through a transformation, it cannot go back to the initial state. If this is not the case and the transformation is reversible, the evolution of the system will not necessarily respect the second principle and move in the direction of an increase in entropy as explained by Klein and Nellis (2012). Reversibility belongs to the world of theory, and irreversibility to the real world. In real life, transfers are irreversible. In finance too, the movements are irreversible. In order to demonstrate that the assumption of irreversibility does hold for financial transaction, let’s follow a descriptive process of the financial engineering operations listed before in Section 3.1:
1. If a risk transfer happened through an Initial Public Offering (IPO), the minority investors can sell back their shares on the secondary market, but at the new market price. The original risk transfer is therefore irreversible.

2. If a risk transfer happened through a Debt Capital issue, the bond or note holder has in theory the option of targeting the assets of the company in case of a credit event. This assures reversibility of the transaction in theory, but it does not hold in reality because of transaction costs. In the same way that a pendulum cannot reach perpetual motion because of air frictions, debt holders are faced with transaction costs when they want to target the assets of the company in order to repay their debt. These transaction costs include but are not limited to: administrative costs, legal costs, and opportunity costs which result from allocating employees and capital to the sole process of getting payed back. Therefore the transfer is irreversible.

3. If a risk transfer happened through an Asset Securitization, investors might be faced with a poor business performance of the assets isolated inside the special purpose vehicle (SPV). Therefore the transfer is irreversible.

4. If a risk transfer happened through a Factoring of Receivables and a credit event materializes on the receivables, two cases are possible.
   • First, if the transfer was done without a recourse option, then the investor might lose capital, proving that the transfer is irreversible.
   • Second, if the transfer was done with a recourse possibility against the parent company, this recourse would require transaction costs as described above for debt holders, proving that the transfer is in reality irreversible.

5. If a risk transfer happened through a Hedging Operation using Derivatives securities, once the risk materializes, the losing party has to pay its counterparty a mandatory financial settlement, implying that the risk transfer was irreversible.

6. If a risk transfer happened through a Structured Product Issue, the structuring risk resulting from underperforming quantitative models used to design the product, rest with the issuer. The risk transfer is irreversible.
7. If a risk transfer happened through an Insurance Policy, once the risk materializes and the insurance company has to pay insurance benefits to the customer, the risk transfer appears to be irreversible.

By reviewing all the possible scenarios, we reach the conclusion that each time the risk transfer is irreversible. If the risk taker does not have the ability to bear a certain risk anymore, he can enter into a countering operation to sell the risk to another counterparty; but the initial transaction stays irreversible. By validating the assumption that transactions are irreversible, we can apply the second principle of thermodynamics to financial engineering, and infer that the evolution of the financial system, goes in the direction of an increase of its entropy. This means that the degree of dispersion of risk inside the financial system is increasing with time.

Rajan (2005) explains how Developments in the financial sector have led to an expansion in its ability to spread risks, how Financial markets have expanded and become deeper…allowing risks to be more widely spread throughout the economy, and how the takeoff – of the credit derivatives – is a testament to how financial innovation has been used to spread traditional risks. Kose et al. (2008) takes a complementary approach by focusing on financial globalization - which can be interpreted as a form of financial innovation and financial engineering, aimed at designing products and solutions to bridge financing and investing gaps on an international level. Kose et al. (2008) demonstrate how in theory, one of the main benefits of financial globalization is that it should allow for more efficient international risk sharing; then move to using a wide range of empirical methods to reach the conclusion that only industrial countries have attained better risk sharing outcomes during the recent period of globalization. Developing countries have, by and large, been shut out of this benefit.

Without financial engineering, the risk of each economic project would simply be borne by its founding shareholders. The entropy, which corresponds to the dispersion of the risk, would be small. All of the risk would only be arranged in one box, with only one stakeholder. But due to an increasing use of financial engineering, many stakeholders would subscribe to a part of this risk – national and international ones. This means that the risk would be distributed on many actors, implying that the number of states in which one can put the system becomes much more important. The entropy of the financial system is therefore increasing with time.
3.3 Principle no. 3: The principle of measurement

The third principle of thermodynamics is a measurement principle. Theorized by Nernst, the third principle gives a numerical anchoring to entropy, so as to calculate the absolute entropy of a body. According to Klein and Nellis (2012) the Nernst principle implies that the entropy of a perfect crystal at zero degrees Kelvin is zero. It thus fixes a benchmark which makes it possible to measure the entropy of the other elements. At the temperature of zero degrees Kelvin, the molecular agitation is reduced to the minimum possible, so that the temperature is as low as possible. At this level, the principle states that for a perfect crystal entropy can be considered as zero.

The same goes for financial engineering: to build products and carry out the calculations required for their construction, a measurement principle must be adopted. This principle makes it possible to set a reference frame from which measurements can be made. As discussed before, we defined the main state variable in financial engineering as risk. It is therefore necessary to set a benchmark for the measurement of financial risk: assume that a certain type of investment carries a zero risk, so that one can quantify the risk contained in other investments. This principle is observed in the Capital Asset Pricing Model (CAPM) of Sharpe (1964) and Lintner (1965a; 1965b) where the required return from a risky asset, is a sum of a risk-free return on an asset considered to be an appropriate reference, and a risk premia aimed at rewarding rational investors for the extra risk assumed. Under the assumptions of the CAPM, the risk-free rate chosen will impact the security valuation in two ways:

1. It will first define the risk-free rate used in the first term of the calculation
2. It will also impact the risk premia since this premium is calculated by subtracting the risk-free rate from the return of risky assets, in a historical or prospective approach

Damodaran (2008) provides a methodology for choosing the appropriate risk-free rate in different market situations. He defines a risk-free asset as an asset which fulfills the following condition: the actual return on the security is always equal to the expected return, which implies that there is no variance of actual returns around the expected return. In order for an asset to respect this assumption of a null variance, two conditions are required:

1. There is no default risk of the security, which implies that the issuer has the ability and the willingness to pay back its promised cash flows on time;
2. There is no reinvestment risk on the security, which implies that the intermediate cash flows received such as coupons can be reinvested in the future at the same interest rate than the original one carried by the security.

If these two conditions are respected the asset can be considered as risk free because the actual return will be equal to the expected return, and as a direct consequence the security actual returns would be uncorrelated with the returns of the market. Damodaran (2008) explains a traditional assumption in financial practice, which is to consider that sovereign debt securities issued in local currency, are the risk-free asset. This assumption is not made because governments are better managed than corporates, but for two other reasons:

1. The revenue base of a state is much larger than that of a firm. If a state faces financial difficulties in repaying financial obligations, it has the ability to create a new mandatory taxation. The government will raise new resources to pay his dues. A company cannot like a state, create a new product and sell it to customers in a mandatory approach, in order to raise new resources. In the real world, this assumption depends on the fluidity of the collaboration process between the executive power (aka the government) and the legislative power (aka the parliament). A lack of collaboration between both can block this lever for the government. In the U.S., a confrontation between the Congress and the White House led to a risky defaulting situation for Treasuries in 2011 and 2013, as the Congress opposed an increase in the U.S. debt ceiling.

2. The state trough the central bank has the ability to issue local currency to repay his debt. So the debt would be repaid at least in nominal terms, at the cost of inflation if the issue is massive. In the real world, this assumption does not hold if the central bank is an independent institution focused on its own objectives such as inflation or interest rate targeting. In cases like the European Union, where the countries constructed a monetary union, the authority of currency issuing has been passed to an independent authority (aka the European Central Bank), blocking this lever for the governments. In the Eurozone crisis of 2010/2011, countries in financial difficulty like Portugal, Italy, Spain, and Greece were not able to respect this assumption, and thus threatened to default.

Damodaran (2008) not only defines the characteristics of a risk-free asset, but also provides a road map for particular market situations. In cases where government bonds cannot be considered as risk
free assets, he recommends using as a proxy the safest local corporate bonds yields after subtracting a default spread from them, or an adjusted international risk-free asset.

Measuring risk correctly in financial engineering is the consequence of a well measured risk-free rate which is the reference, and a well measured risk premia. Measuring risk correctly is fundamental because it determines the cost of capital, which is the return required by investors. This cost of capital will be used to value the new financial products and solutions designed. When the third principle of financial engineering is not respected, which means that the risk is not correctly measured, this leads to significant imbalances in the markets:

- If the risk is underestimated, the cost of capital is too low, and prices are overvalued. Scherbina (2013) defines asset bubbles as a situation where the prices of securities are higher than the fundamental prices as reflected by the sum of their future discounted cash flows, and remain that way for an extended period of time before collapsing. She also provides a literature review of the different models used to explain the dynamics of asset bubbles, and overvaluation is an input factor retrieved in many models. The explosion of a bubble may be seen as the moment where previously undervalued risks are being priced more efficiently in asset prices.

- Conversely, if the risk is overestimated, the cost of capital is too high, and prices are undervalued. Risks can be overvalued in situations where financial markets are stressed, and where information asymmetry increases between participants leading to a freeze of capital market transactions. After the Lehman Brothers collapse during the 2008 crisis, information asymmetry increased between financial agents leading to freezes on the monetary market. Abbasi et al. (2013) illustrate the freeze on the European monetary market, explaining how loans decreased on the long-term segment, and how risk premias jumped dramatically. The fundamentals alone were not able to explain this huge rise, leaving room for some mispricing due to the increase in risk aversion following the increase in information asymmetry. These stressed situations where risks are overvalued can start destructive self-fulfilling prophecies, where investors are going to flee from an asset class, thereby creating a panic sell-off movement and initiating or exacerbating the crisis. These self-fulfilling prophecies play a major role in many types of financial crises: Flood and Marion (1996) explore their role in currency crises. Diamond and Dybvig (1983) explore their role in banking crises. Cole and Kehoe (1996) and Gärtner and Griesbach (2012) explore their role in sovereign debt crises.
The importance of measuring the risk appropriately stems from the fact that under or overvaluation can lead to price bubbles and financial crises. Reinhart and Rogoff (2009) illustrate the severe macroeconomic consequences which take place in the aftermath of financial crises. According to their classification, these consequences fall into three categories: first. a sudden collapse of asset market prices; second. a banking crisis leading to a decline in output and employment; and third an explosion in real government debt. In order to avoid the severe macroeconomic consequences of financial crises, Jones (2014) provides a two-pillar surveillance framework for identifying speculative bubbles: first. a price pillar based on monitoring the overvaluation of asset prices as compared to fundamentals; second. a quantities pillar based on monitoring the quality and quantity of new securities issuance, trading volumes, investor fund flows, and surveys of investor’s expectations.

For financial engineering innovations to be sustainable over time, they must respect the third principle, which is a measurement principle: the risk must be reasonably quantified. If it is overestimated or underestimated, it will sooner or later drive a market adjustment, calling into question the products and solutions designed. If financial risk is measured correctly and transparently, this leads to a proper valuation of financial products. If this condition is integrated, then the financial engineering work respects the third principle and will be more sustainable. In order to demonstrate this, let us follow as in Section 3.1 an exhaustive descriptive process:

1. Performing initial public offerings at overvalued prices, lead to a financial bubble as attested by DeLong and Magin (2006) for the dot-com bubble in 2000. The subsequent financial crash puts into doubt all the benefits of the previous financial engineering accomplished through many primary and secondary listings.

2. If debt capital issues are mispriced, this would lead to a stressful situation once the market starts incorporating the new information and repricing the securities. If material information was hidden voluntarily by the arrangers of the operation in order to diminish the interest rates on the securities and succeed in the placement, the appearance of this information can trigger covenants in the contract, possibly implying the immediate debt payback. In both cases, this would put into doubt the benefits of the financial engineering accomplished to structure the issues. This case can be illustrated by the Greek sovereign debt crisis: Gibson et al. (2014) explain how risk spreads between
the German and the Greek debts decreased significantly after the adhesion of Greece to the Eurozone system, but the information about the Greek public finances was flawed, especially concerning the budget deficit. When it appeared to the market in October 2009 that the deficit from the current year would be twice the projected 6% of GDP, the spreads started rising, entering into an iterative process made of spreads rises, rating downgrades, and further spread hikes. This is a classic case of repricing which casts doubt about the financial engineering performed before, note only on the debt securities issues, but also on swaps instruments used by the Greek government to reduce the apparent size of the public debt, and respect the criteria required to enter the Eurozone system in 2001.

3. Asset securitization was at the heart of the Subprimes Crisis of 2008. The quality of the mortgages securitized was not reflected in the rating of the securities issued, and thus not incorporated in the valuations. Once risky mortgages started defaulting, the securities started to be repriced. Acharya et al. (2009) explain how there was just a fundamental mispricing in capital markets – risk premia were too low and long-term volatility reflected a false belief that future short-term volatility would stay at its current low levels. This mispricing necessarily implied low credit spreads and inflated prices of risky assets. This situation – due to many factors one of them being the mispricing of securitized assets – put into doubt the benefits of the financial engineering accomplished, and casted doubt on the benefits of securitization once the Subprime crisis exploded. These financial products would have been more sustainable had they been well priced in the first step, to reflect the true risk they were bearing.

4. A factoring of receivables which is mispriced, will put into doubt the future operations once the factor takes in account the initial asymmetry of information. This will lead to questioning the benefits of financial engineering behind the factoring operations. This can be illustrated by frauds like Enron. Kuhn and Sutton (2006) explain how Enron systematically revised the bad debt reserve calculation downward in order to boost the valuation for receivables that were subsequently factored. By using this technique and others such as operating leases and unconsolidated entities, the firm’s debt appeared lower than it really was, showing investors a healthier balance sheet. After this scandal, many of these operational financial engineering techniques aimed at managing liquidity, started attracting public scrutiny, and casting doubt about their true benefits.

5. The issue of derivatives which are mispriced and misconceived for the client can have severe consequences. This can be illustrated by the Libor Scandal. Hou and David (2014) explain how the Libor is used to value many financial securities, of which derivative contracts such as swaps,
forwards and futures. It appeared to authorities in 2008 and to the public in 2012 that the Libor was being manipulated by a pool of large international banks, in order to manipulate the valuation of derivative contracts. This scandal, just a few years after the Subprime crisis, casted once again another doubt on the benefits of financial engineering.

6. The issue of structured products which are mispriced or misconceived for the client will also lead to severe consequences. Geckeler (1996) explains how structured notes contributed to the bankruptcy of municipal funds - the most popular of them being the failure of Orange County Municipal Fund in 1994, which was the largest government failure up to that date. The consequence of this was to cast doubt on the benefits of financial engineering: Geckeler (1996) explores the suitability of using derivatives for municipal investors.

7. The issue of insurance policies which are mispriced will lead into an insolvency of the insurance company, questioning the financial engineering behind the operation. Sjostrum (2009) explains how AIG moved from being a traditional insurance company to an insurance company fully involved in the new techniques of financial engineering. AIG financial division started issuing Credit Derivative Swaps (CDS) to sell protection to investors on Collateralized Debt Obligations (CDOs) based on securitized subprime mortgages, in order to collect the premiums. The bankruptcy of AIG, the largest American insurance company, came from its failure to honor the insurance promises sold through the CDSs. AIG was underestimating the risk of the CDSs it did issue.

Through this exhaustive descriptive process, we reach the conclusion that mispricing products and solutions of financial engineering will sooner or later result in a market adjustment, casting doubt on the benefits the financial innovations developed before. Thus, pricing the securities in the right way, is a key factor for the sustainability of financial engineering products and solutions.

4. The three axiomatic laws of finance

We have demonstrated in Section 3 how sustainable financial engineering requires three principles to be respected:

1. The principle of conservation, which implies that financial engineering does not affect the stock of risk but only provides tools to allocate risk between agents
2. The principle of evolution, which implies that the risk entropy of the financial system increases with time

3. The principle of measurement, which implies that any product or solution designed by financial engineering must correctly measure the risk - which requires fixing a reference

According to Krebs (2008) principles are observable and reproducible phenomena, but they do not offer explanations to understand why the phenomena in question occur. Behind every principle lies a fundamental law that explains it. Here we follow an explanatory approach in order to illustrate the fundamental laws of finance, which put the three principles observed in Section 3 in motion. These laws are described as axiomatic. The Oxford Dictionary defines an axiom as: a proposition which is regarded as being established, accepted, or self-evidently true. We will demonstrate that the three fundamental laws we propose are axiomatic, by showing that they have historically always been accepted by practitioners of the financial industry.

4.1 Axiomatic law no. 1: The future is always uncertain

Why does the conservation principle state that financial engineering techniques never decrease the risk contained in a project, and only allow an allocation of this stock of risk? Because the risk contained in an asset can be divided according to the CAPM of Sharpe (1964) and Lintner (1965a, 1965b) into systematic risk and idiosyncratic risk. This implies that risk is intrinsically dependent of the economic asset or project, and the financial market conditions; so financial engineering techniques cannot modify the risk of an economic asset or the financial market conditions.

From a probabilistic perspective, financial engineering tools cannot decrease the risk contained in a project, because they cannot make the future more predictable. The future is always uncertain, and what financial engineering enable is to reallocate gains and losses according to new scenarios agreed in advance. If one wants to make the future more predictable, the only solution is to act directly on an operational level on the economic project, in order to make the future cash flows more probable, thereby decreasing the variance of future returns around the expected return.

Knight (1921) defines the difference between uncertainty and risk: an event is risky if its randomness can be measured by probabilities, an event is uncertain if its randomness cannot be measured by probabilities. We formulate this first law using the word uncertain and not risky for a reason: an uncertain world is one where some events are known to be random and are approached by
probabilities, and other events are known to be random and cannot be predicted. This is closer to reality: arguing that the future is always risky would imply that all the random events have been approached using a probabilistic approach, which is a doubtful assumption.

This law is axiomatic because investors have always considered that the future cash flows to be received are risky or even uncertain. This can be illustrated by the fact that discounting cash flows is a very old technique in the history of finance. Discounting future cash flows using discount rates is the standard method in finance to take into account the fact that the future is not predictable. When discounting future cash flows, Parsons (2006) show that a nominal discount rate can be broken down into the expected inflation - which aims to offer investors a conservation of their purchasing power -, a real risk-free rate - which aims to compensate investors for the intertemporal substitution between investing and consuming -, and a risk premium - aimed at compensating investors for the risk associated with the future cash flows. And on this issue, Parker (1968) provides a long history of the DCF methodology before the 1950s. She argues that the first pillar of discounting cash flows - which is the notion of compound interest - can be found in Old Babylonian period (1800-1600 B.C.) in Mesopotamia. Many mathematical books dealing with discounting interest cash flows, circulated in Italy in the 13th and 14th century when banking became a notable activity. Through this long history, we can take as an axiomatic law the fact that financial agents have always considered the future to be uncertain, and thus have always tried to include this element in their financial calculations.

4.2 Axiomatic law no. 2: Capital markets drive toward equilibrium

Why does the evolution principle state that the risk entropy of the financial system is increasing with time? The answer lies in the fact that the usage of financial engineering is increasing with time: financial innovation, financial disintermediation, financial penetration, etc. The following question is why does the usage of financial engineering increase with time? The answer lies in the dynamics of capital markets.

Capital markets are subject to the same law of demand and supply than other scarce resources markets. The dynamics of supply and demand in order to reach equilibrium are axiomatic in economics because these dynamics have been observed since ancestral times. Chendroyaperumal (2010) explains how supply and demand which drives market equilibrium has been mentioned in an
Indian text – the Thirukkural – written 2,000 years ago. Hosseini (2003) explores the contribution of Muslim scholars in the medieval age to the economics theory and especially the market mechanism. Classical economics books mentioning the same law then followed such as Locke (1691), Steuart (1767), Smith (1776), and Marshall (1890). The very far origin of this law proves that the law of supply and demand is axiomatic.

In the field of capital markets, the law of supply and demand does apply. Capital is supplied in the financial market, and capital is demanded, resulting in an equilibrium price for capital, which is an interest rate. If one concentrates on a single financial agent, this agent will have resources – his own capital or borrowed capital – and will invest these resources in assets. Three situations are possible:

A. If Return on Capital < Cost of Capital. The agent is destroying value, this situation is in disequilibrium and will trigger adjustments to reach a new equilibrium.

B. If Return on Capital > Cost of Capital. The agent is creating value, this situation is in equilibrium.

C. If Return on Capital >> Cost of Capital. The agent may be taking excessive risk with risk averse resources, this situation is in disequilibrium and will trigger adjustments to reach a new equilibrium.

In what form can the adjustments in case A and C happen? Two outcomes are possible in order to resolve this disequilibrium:

• Either there is a market correction in order to reach a new equilibrium: this means that unsatisfied clients are withdrawing their deposits from the financial agent. and go on to offer their capital to another financial agent who better fits their requirements – either of earning a higher return in case A or bearing less risk in case C.

• Either the financial agent notices this disequilibrium situation, and attempts to solve it in order to avoid a market correction. In case A he will buy risk in financial markets, and in case C he will sell risk in financial markets.

The survival of financial agents requires them to follow preemptive adjustment in order to avoid penalizing market adjustments. The way to do it is to use the full benefits of financial engineering and financial innovation. In order to increase or decrease his risk exposure, a financial agent can use...
existing financial engineering products, or ask for customized solutions. If he succeeds in balancing the returns on his assets and the requirements of his liabilities, he will avoid a market adjustment. Thus, the increasing use of financial engineering by agents in order to secure their survival, drives a higher dispersion of risks between agents, reflecting the rising risk entropy of the financial system. We formulate the axiomatic law no.2 in finance as follow: capital markets strive toward equilibrium.

4.3 Axiomatic law no. 3: Return is always proportional to risk

Why does the measurement principle state that risk must be properly assessed, using a suitable benchmark, in order to design sustainable financial engineering solutions? We have demonstrated in Section 3.3 that an undervalued or overvalued risk sooner or later leads to a market adjustment, casting doubts about the benefits of the previous financial engineering accomplished. But why does this principle work? Because the third axiomatic law of finance is that return is always proportional to risk.

The fact that return is proportional to risk stems from the hypothesis of Rational Economic Man (REM). Pompian (2011) defines a REM as an investor who is a self-interested investor, who makes decisions possessing perfect information, assigns probabilities to all the possible events, and makes decisions in order to maximize his utility. The consequence of being a self-interested utility maximizer is that REM is considered to be risk averse. This implies that a REM requires an extra return in order to assume an extra risk, which explains why return is always proportional to risk.

The REM assumption is axiomatic because of its long history in economics. Morgan (1996) provides a history of the REM hypothesis, showing how this concept can be traced back to the 18th century with the work of Bernard Mandeville, and the 19th century with the work of Smith. Ricardo. Malthus. Bagehot. Jevons. Edgeworth. Bentham. Marshall. Pareto, and most notably John Stuart Mill. The assumptions of REM are challenged by the theory of behavioral finance; Pompian (2011) provides a description of the theory of bounded rationality which relaxes the assumptions of the perfect rationally utilitarian theory. One of the consequences of this relaxation is the Friedman-Savage double inflexion utility function, which implies that investors are not always risk averse: they can be risk averse in some context, and then turn into being risk seeker in another context. We argue that this stands only on a micro individual agent level and for a limited period of time - we use the word limited and not short, because arbitrage constraints may slowdown the market adjustment.
On a long time horizon, the return of asset classes becomes proportional to their risk, thereby demonstrating a risk aversion profile where investors need an extra-return to assume an extra-risk. Raymond James & Associates (2011) provide information about returns and risk of different U.S. asset classes in the long run from 1926 to 2010. This information is illustrated in Table 1. Risk is measured by the standard deviation of returns. The least risky asset class – treasury bills – with the lowest standard deviation earns the lowest return. The most risky asset class – small stocks – with the highest standard deviation earns the highest return. The correlation between risk and return is positive: the more an asset is risky, the more it earns a higher return in the long run. Thereby, this proves that investors require higher returns in the long return for assuming higher risks, demonstrating that the risk aversion assumption holds for long periods of time.

<table>
<thead>
<tr>
<th>Asset classes</th>
<th>Compound annual return</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treasury Bills</td>
<td>3.6%</td>
<td>3.1%</td>
</tr>
<tr>
<td>Government Bonds</td>
<td>5.5%</td>
<td>9.5%</td>
</tr>
<tr>
<td>Large Stocks</td>
<td>9.9%</td>
<td>20.4%</td>
</tr>
<tr>
<td>Small Stocks</td>
<td>12.1%</td>
<td>32.6%</td>
</tr>
</tbody>
</table>

As the assumption of risk aversion holds in the long run, we formulate the axiomatic law no.3 as follow: return is always proportional to risk. Because of this axiomatic law, the principle of measurement holds: risk and thus required return must be appropriately valued; if not, an undervaluation or overvaluation of risk will eventually be corrected through a market adjustment, thereby questioning the previous financial engineering.

5. The three construction rules in financial engineering

In Section 3 we detailed the three principles of financial engineering and in Section 4 we explored the three axiomatic laws of finance which put the principles into motion. Any financial engineering design which does not take into account the three principles, will eventually fail casting doubts about the benefits of financial innovation. Thus, in this section we argue that by following three
construction rules in financial engineering, the products and solutions will respect the three principles. The implication of this is that the solutions designed will be more sustainable, providing larger societal benefits, increasing financial stability by diminishing the risk of financial crises. In this section, we will illustrate each rule with evidences from the Subprimes crisis of 2008. The three construction rules in financial engineering are as follow.

5.1 Construction rule no. 1: Inform

In order to respect the first principle of risk conservation, we must ask the question when is this principle not respected and does financial engineering crumble down? This happens when information about risk is not symmetrical, fair, and complete between financial engineers (the conceiver of the product or solution) and the financial agents (the clients). A discovery of hidden or misrepresented information, produces a stress situation here financial engineering is questioned. An example from the Subprimes crisis of 2008 is given by Benmelech and Dlugosz (2010), where they explore the crucial role of rating agencies in the financial crisis. Complex Collateralized Debt Obligation structures (CDOs), which were exposed to subprime mortgages, were still rated AAA, the highest possible rating. These ratings proved to be incorrect because during the crisis nearly one-third of the downgrades concerned tranches which were rated AAA by Moody’s. According to Benmelech and Dlugosz (2010): Investors placed too much faith in the rating agencies which, to put it mildly, failed to get it right. If investors were better informed about the underlying risks expositions of these complex structured products, it is safe to say that some investors would have questioned their exposition. Information is the main tool to respect the first principle of risk conservation; an investor must fully understand two elements:

a. Understand the risk he is buying

b. Understand the spread of the risk he is selling between the other agents. This enables the investor to understand the critical moment where some kind of risk he sold, will reverse back to him. For example, by subscribing to an insurance product and deciding to sell a certain risk, the investor must understand under which conditions the insurance company will stop assuming the risk (special contract clauses. insurance celling amount. etc.) , and let the risk reverse back to him. Another example: an investor in a subordinated bond issue, must not only understand the company’s risk he
is investing in, but also understand in which conditions will the cash flows be captured by the senior tranche service, leaving him in a defaulting situation.

5.2 Construction rule no. 2: Regulate

In order to respect the second principle of evolution, we must ask the question when is this principle not respected and does financial engineering crumble down? This happens when an agent holds too much risk than his liabilities allow him to do so. The spread of financial engineering is continuous because it enables agents to correct disequilibrium situations of their assets and liabilities in a preemptive manner, thereby avoiding market corrections. The consequence of this is the increase in the risk entropy of the financial system. For the system to be stable, we must make sure that this risk distribution is optimal. While reaching this optimal allocation is the role of the capital market, society must make sure that some agents do not use financial engineering to unbalance their situation, rather than balancing it. An agent who has risk averse resources, should not get exposed to higher risks than his situation authorizes. Thus, this directly calls for micro-regulation of financial agents. The goal is to set a ceiling on the risk bearing capacity of each agent, according to the structure of his resources. The goal of this regulation is to make sure that financial engineering is used in the proper way: to strive toward equilibrium rather than getting away from it. Evidence from the Subprimes meltdown in 2008 confirms the fact that financial engineering was used by some agents to move away from equilibrium rather than toward it. Dymski (2010) explains how many of the megabanks were themselves over-exposed in the sub-prime market and consequently undercapitalized. This shows how these banks did not respect the second principle by increasing their risk exposition too much. Systemic regulation became lacking once the crisis erupted. Acharya at al. (2009) explain how there was little information and disclosure about such instruments – securitized subprime products – and who was holding them, and add the lack of transparency on what financial institutions were holding and how much of the conduit loss would get passed back to the sponsoring institutions caused the entire market to shut down. This clearly shows that there was a problem of micro-regulation; regulators were not fully pricing the risk exposure of each agent, therefore letting them bypass the limitation.

5.3 Construction rule no. 3: Value

In order to respect the third principle of measurement, we must ask the question when is this principle not respected and does financial engineering crumble down? This happens when valuations are not
efficient, because they underestimate or overestimate the underlying risks of the asset. We have demonstrated in section 3.3 how underestimating the cost of capital can lead to inflated valuation, to bubbles and crashes; and how an overestimated cost of capital can increase risk aversion in stressed markets and start self-fulfilling prophecies. Acharya et al. (2009) provide evidence about market mispricing during the Subprime crisis of 2008, a factor between others which contributed to the meltdown. The construction rule is straightforward: valuation of financial engineering products and solutions must be fair and efficient, in order to ensure their sustainability over different market conditions.

6. Summary and concluding remarks

By following an econophysics approach, we applied the three principles of thermodynamics into the field of finance. In order to do that, we gave a broad definition to financial engineering, one which includes corporate finance solutions and financial markets solutions. The broad definition we gave to financial engineering is close to the general concept of financial innovation. This definition was intentionally broad in order to follow a descriptive research methodology, where we explore the possible scenarios in an exhaustive manner in order to reach a conclusion. After describing the application of the principles of thermodynamics in finance which enable us to formulate the three principles of financial engineering – the conservation principle of risk, the evolution principle of risk and the measurement principle of risk – we move to an explanatory research methodology in order to explain the laws which put the principles into motion. We formulate and explore the three axiomatic laws of finance: the future is always uncertain, capital markets drive toward equilibrium, and return is always proportional to risk. In the last section, we build on the three principles enunciated to propose three construction rules for financial engineering. These rules – inform, regulate, and value – enable financial innovations to respect the three principles of financial engineering, thereby increasing their sustainability trough different market conditions, and increasing financial stability by avoiding financial crises. Future research will require back testing the three construction rules proposed on a large sample of financial crises, in order to infer if these rules would have significantly contributed to avoid the meltdown, based on an empirical approach.

Figure 4 provides a summary of the three axiomatic laws of finance, the three principles of financial engineering, and the three construction rule of financial engineering.
Axiomatic laws

- The future is always uncertain
- Capital markets drive toward equilibrium
- Return is always proportional to risk

Principles

- Conservation principle of risk
- Evolution principle of risk
- Measurement principle of risk

Rules

- Inform
- Regulate
- Value

Fig. 4. Summary of the axiomatic laws, principles, and rules of financial engineering

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