Successive Joint Torts: Conditions for Efficiency

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An important subclass of torts is that of successive joint torts. In a successive joint tort, in the first instance the victim suffers harm on account of interaction with a tortfeasor, which subsequently is aggravated because of interaction with another tortfeasor. There can of course be no aggravation if there is no accident in the first instance. A car driver inflicting an injury on a pedestrian, and the aggravation of injury during transportation to the hospital because of negligence or during treatment because of doctor's negligence, is an example of a successive joint tort.

Successive joint torts are to be distinguished from simultaneous joint torts. In a simultaneous joint tort the victim suffers a single indivisible injury as a result of activities of two or more tortfeasors.[1]

The first analysis of successive joint torts from the perspective of economic efficiency was carried out by Landes and Posner (1987). They analysed the following rule for assigning liabilities of the parties:

(i) If both the injurers and the victim are nonnegligent then the losses occurring in both the stages are borne by the victim.

(ii) If both injurers are nonnegligent and the victim is negligent then the losses occurring in both the stages are borne by the victim.

(iii) If the injurer of the first stage is negligent, and the injurer of the second stage and the victim are nonnegligent, then the losses of both the stages are borne by the first injurer.

(iv) If the injurer of the second stage is negligent, and the injurer of the first stage and the victim are nonnegligent, then the loss of the first stage is borne by the victim and the loss of the second stage is borne by the second injurer.

(v) If the first injurer and the victim are negligent and the second injurer is nonnegligent then the losses of both the stages are borne by the victim.

(vi) If the second injurer and the victim are negligent and the first injurer is nonnegligent then the loss of the first stage is borne by the victim and the loss of the second stage is

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[1]For economic analysis of simultaneous joint torts, see Landes and Posner (1980, 1987), Kornhauser and Revesz (1989), Tietenberg (1989), Miceli and Segerson (1991), and Jain and Kundu (2006).

borne by the second injurer.
(vii) If both injurers are negligent and the victim is nonnegligent then the loss of the first stage is borne by the first injurer and the loss of the second stage is borne by the two injurers in some proportions.
(viii) If both the injurers and the victim are negligent then the loss of the first stage is borne by the victim and the loss of the second stage is borne by the two injurers in some proportions.

Schematically the rule considered by Landes and Posner can be represented as follows:

Victim	First Injurer	Second Injurer	Liability for First Stage Loss on	Liability for Second Stage Loss on
Nonnegligent	Nonnegligent	Nonnegligent	Victim	Victim
Negligent	Nonnegligent	Nonnegligent	Victim	Victim
Nonnegligent	Negligent	Nonnegligent	First Injurer	First Injurer
Nonnegligent	Nonnegligent	Negligent	Victim	Second Injurer
Negligent	Negligent	Nonnegligent	Victim	Victim
Negligent	Nonnegligent	Negligent	Victim	Second Injurer
Nonnegligent	Negligent	Negligent	First Injurer	Both Injurers in Some Proportions
Negligent	Negligent	Negligent	Victim	Both Injurers in Some Proportions

Landes and Posner have shown that the above rule is efficient.

In this paper, instead of analysing particular rules for assigning liabilities for harms in cases of successive joint torts, we consider the problem generally and analyse the totality of all liability rules for successive joint torts. Formally, a liability rule for successive joint torts is a rule that determines (i) in case of first accident, the liability shares of the victim and the first injurer on the basis of the extents of negligence of the victim and the first injurer; and (ii) in case of second accident, the liability shares of the victim and the two injurers on the basis of the extents of negligence of the victim and the two injurers. We show that a liability rule for successive joint torts is efficient if the following condition is satisfied: if one of the victim and the first injurer is negligent and the other nonnegligent, then the entire accident loss resulting from interaction between the victim and the first injurer is to be borne by the negligent individual; and if one of the victim and the two injurers is negligent then no nonnegligent individual is to bear any part of the accident loss resulting from interaction between the victim and the second injurer. This condition has been termed in the paper as negligence liability for successive joint torts (NL-SJT).

A subclass of the class of all liability rules for successive joint torts is that of simple liability rules for successive joint torts. A simple liability rule for successive joint torts apportions the accident losses solely on the basis of negligence or otherwise of individuals; the extents of negligence are not taken into account. The rule analysed by Landes and Posner is also a simple liability rule for successive joint torts. It turns out that a simple liability rule for successive joint torts is efficient if and only if it satisfies NL-SJT.

The paper is divided into four sections excluding this section. The first section presents the framework within which the analysis of the paper has been carried out. The framework is essentially that of the standard tort model of interaction between a victim and an injurer first developed by Brown (1973)[2], suitably modified for analysing successive joint torts. The second section establishes that a sufficient condition for a liability rule for successive joint torts to be efficient is that it satisfy the condition of NL-SJT. The third section contains the statement and the proof of the theorem that a simple liability rule for successive joint torts is efficient if and only if it satisfies the condition of NL-SJT. The last section contains some remarks regarding the question of necessity of NL-SJT for efficiency of any liability rule for successive joint torts.

1 The Framework

We consider accidents resulting from successive joint torts involving one victim (individual 1) and two injurers, individual 2 being the injurer in the first accident, and individual 3 the injurer in the second accident. The parties will be assumed to be strangers to each other and risk-neutral. We denote by $c_i \geq 0, i = 1, 2, 3$, the cost of care taken by individual i. We assume that $c_i, i = 1, 2, 3$, is a strictly increasing function of level of care of individual i. This of course implies that $c_i, i = 1, 2, 3$, itself can be taken as an index of level of care of individual i.

Let

$C_i = \{c_i \mid c_i$ is the cost of some feasible level of care which can be taken by individual $i\}, i = 1, 2, 3$.

We assume $0 \in C_i, i = 1, 2, 3$. (A1)

$c_i = 0, i = 1, 2, 3$, will be identified as no care by individual i. Assumption (A1) merely says that taking no care is always a feasible option for each individual.

We denote by π_1 the probability of accident in the interaction between individuals 1 and

[2]See also Landes and Posner (1987), Shavell (1987), Miceli (1996), Jain and Singh (2002), Jain (2015), among others.

2, and by H_1 the quantum of loss in case of accident in the interaction between individuals 1 and 2. Both π_1 and H_1 will be assumed to be functions of care levels of individuals 1 and 2; $\pi_1 = \pi_1(c_1, c_2), H_1 = H_1(c_1, c_2)$. Let $L_1 = \pi_1 H_1$. Thus L_1 is the expected loss resulting from the interaction between individual 1 and 2, and is a function of care levels of individuals 1 and 2; $L_1 = L_1(c_1, c_2)$.

There can be no accident in the second stage if there is no accident in the first stage. Let π_2 be the conditional probability of second accident (conditional on the occurrence of first accident) involving interaction between individuals 1 and 3, and H_2 the quantum of loss in case of accident in the interaction between individuals 1 and 3. Both π_2 and H_2 will be assumed to be functions of care levels of all three individuals 1,2,3. Let $L_2 = \pi_1\pi_2 H_2$. Thus L_2 is the expected loss resulting from the interaction between individual 1 and 3, and is a function of care levels of all three individuals 1,2,3; $L_2 = L_2(c_1, c_2, c_3)$.[3]

We assume:
$(\forall c_1, c_1' \in C_1)(\forall c_2, c_2' \in C_2)[[c_1 > c_1' \rightarrow L_1(c_1, c_2) \leq L_1(c_1', c_2)] \wedge [c_2 > c_2' \rightarrow L_1(c_1, c_2) \leq L_1(c_1, c_2')]]$. (A2)
and
$(\forall c_1, c_1' \in C_1)(\forall c_2, c_2' \in C_2)(\forall c_3, c_3' \in C_3)[[c_1 > c_1' \rightarrow L_2(c_1, c_2, c_3) \leq L_2(c_1', c_2, c_3)] \wedge [c_2 > c_2' \rightarrow L_2(c_1, c_2, c_3) \leq L_2(c_1, c_2', c_3)] \wedge [c_3 > c_3' \rightarrow L_2(c_1, c_2, c_3) \leq L_2(c_1, c_2, c_3')]]$. (A3)

In other words, it is assumed that a larger expenditure on care by individual 1 or 2, given the expenditure on care by the other individual, does not result in higher expected loss for the victim (individual 1) in the first interaction; and that a larger expenditure on care by an individual, given the expenditures on care by the other two individuals, does not result in higher expected loss for individual 1 in the second interaction.

Total social costs (TSC) are defined to be the sum of costs of care by individuals 1,2,3, individual 1's expected loss in the first stage, and individual 1's expected loss in the second stage; $TSC = c_1 + c_2 + c_3 + L_1(c_1, c_2) + L_2(c_1, c_2, c_3)$. Let $M = \{(c_1', c_2', c_3') \in C_1 \times C_2 \times C_3 \mid c_1' + c_2' + c_3' + L_1(c_1', c_2') + L_2(c_1', c_2', c_3')$ is minimum of $\{c_1 + c_2 + c_3 + L_1(c_1, c_2) + L_2(c_1, c_2, c_3) \mid c_1 \in C_1 \wedge c_2 \in C_2 \wedge c_3 \in C_3\}\}$. Thus M is the set of all costs of care configurations (c_1', c_2', c_3') which are total social costs minimizing. It will be assumed that:
C_1, C_2, C_3, L_1 and L_2 are such that M is nonempty. (A4)

In order to characterize an individual's level of care as negligent or otherwise a reference

[3]Landes and Posner assume π_2 to depend only on the care level c_3 of individual 3. It should be noted that even if π_2 and H_2 are assumed to be functions of c_3 only, L_2 would still be a function of c_1, c_2, c_3.

point (the due care level) for the individual needs to be specified. Let $c_i^* \in C_i$ be the due care level for individual $i; i = 1, 2, 3$. We define nonnegligence functions $p_i, i = 1, 2, 3$, as follows:

$p_i : C_i \mapsto [0, 1]$ such that

$$\begin{aligned} p_i(c_i) &= \tfrac{c_i}{c_i^*} \quad \text{if } c_i < c_i^*; \\ &= 1 \quad \text{if } c_i \geq c_i^*. \end{aligned}$$

$p_i, i = 1, 2, 3$, would be interpreted as proportion of nonnegligence of individual i. Individual $i, i = 1, 2, 3$, would be called negligent if $p_i < 1$; and nonnegligent if $p_i = 1$.

A liability rule for successive joint torts is a rule which specifies the proportions in which the victim (individual 1) and the injurer of the first stage (individual 2) are to bear the loss to the victim, in case of occurrence of accident in the first stage, as a function of proportions of nonnegligence of the victim and the injurer of the first stage; and specifies the proportions in which the victim (individual 1) and the two injurers (individuals 2 and 3) are to bear the loss to the victim, in case of occurrence of accident in the second stage, as a function of proportions of nonnegligence of the victim and the two injurers. Formally, a liability rule for successive joint torts is a function f from $[0, 1]^3$ to $[0, 1]^5$, $f : [0, 1]^3 \mapsto [0, 1]^5$, such that: $f(p_1, p_2, p_3) = (x_1, x_2, y_1, y_2, y_3)$, where x_1 and x_2 denote the proportions in which the accident loss of the first stage is to be apportioned between individual 1 and individual 2 respectively, y_1, y_2 and y_3 denote the proportions in which the accident loss of the second stage is to be apportioned among individuals 1, 2, and 3 respectively, $x_1 + x_2 = 1$, and $y_1 + y_2 + y_3 = 1$.

A subclass of the class of liability rules for successive joint torts, to be called the class of simple liability rules for successive joint torts, is defined as follows:

A liability rule for successive joint torts is a simple liability rule for successive joint torts iff $(\forall (p_1', p_2', p_3') \in [0, 1]^3)(\forall N' \subseteq \{1, 2, 3\})[(\forall j \in N')(p_j' < 1) \rightarrow f(\forall i \in \{1, 2, 3\}(p_i = p_i')) = f(\forall i \in \{1, 2, 3\} - N')(p_i = p_i') \wedge (\forall i \in N')(p_i = 0)]$.

Thus a simple liability rule for successive joint torts apportions the accident losses solely on the basis of negligence or otherwise of individuals; the extents of negligence are not taken into account. A simple liability rule for successive joint torts therefore can be viewed as a function from $\{0, 1\}^3$ to $[0, 1]^5$.

Let f be a liability rule for successive joint torts. Then, for any proportions of nonnegligence (p_1, p_2, p_3) of the individuals, f assigns the proportions $(x_1, x_2, y_1, y_2, y_3)$ in which the accident losses to the victim are to be borne by the individuals in case of occurrence of accidents. An application of the liability rule consists of specification of $C_1, C_2, C_3, L_1, L_2, (c_1^*, c_2^*, c_3^*) \in C_1 \times C_2 \times C_3$. Once $C_1, C_2, C_3, L_1, L_2, (c_1^*, c_2^*, c_3^*) \in$

$C_1 \times C_2 \times C_3$ have been specified, for any configuration of costs of care (c_1, c_2, c_3) by the three individuals, proportions of nonnegligence (p_1, p_2, p_3) are uniquely determined. The liability rule then uniquely determines the liability proportions $(x_1, x_2, y_1, y_2, y_3)$ corresponding to (p_1, p_2, p_3).

The expected costs of individual $i, i = 1, 2, 3$, at (c_1, c_2, c_3) will be denoted by $EC_i(c_1, c_2, c_3)$. We have:
$EC_1(c_1, c_2, c_3) = c_1 + x_1(p_1(c_1), p_2(c_2))L_1(c_1, c_2) + y_1(p_1(c_1), p_2(c_2), p_3(c_3))L_2(c_1, c_2, c_3)$
$EC_2(c_1, c_2, c_3) = c_2 + x_2(p_1(c_1), p_2(c_2))L_1(c_1, c_2) + y_2(p_1(c_1), p_2(c_2), p_3(c_3))L_2(c_1, c_2, c_3)$
$EC_3(c_1, c_2, c_3) = c_3 + y_3(p_1(c_1), p_2(c_2), p_3(c_3))L_2(c_1, c_2, c_3)$.

Let f be a liability rule for successive joint torts. f is defined to be efficient for a given application $< C_1, C_2, C_3, L_1, L_2, (c_1^*, c_2^*, c_3^*) \in C_1 \times C_2 \times C_3 >$ iff $(\forall(\overline{c}, \overline{d}) \in C \times D)[(\overline{c}, \overline{d})$ is a Nash equilibrium $\rightarrow$ $(\overline{c}, \overline{d}) \in M]$ and $(\exists(\overline{c}, \overline{d}) \in C \times D)[(\overline{c}, \overline{d})$ is a Nash equilibrium]. In other words, a liability rule for successive joint torts is efficient for a particular application $< C_1, C_2, C_3, L_1, L_2, (c_1^*, c_2^*, c_3^*) \in C_1 \times C_2 \times C_3 >$ iff (i) every $(\overline{c}, \overline{d}) \in C \times D$ which is a Nash equilibrium is total social costs minimizing, and (ii) there exists at least one $(\overline{c}, \overline{d}) \in C \times D$ which is a Nash equilibrium. A liability rule is defined to be efficient with respect to a class of applications iff it is efficient for every application belonging to that class.

We denote the set of all applications $< C_1, C_2, C_3, L_1, L_2, (c_1^*, c_2^*, c_3^*) \in M >$ satisfying assumptions A(1)-A(4) by $\mathcal{A}$.

Next we define the condition of negligence liability for successive joint torts (NL-SJT).
A liability rule for successive joint torts f satisfies the condition of NL-SJT iff
$[(\exists i \in \{1, 2\})(p_i < 1) \rightarrow (\forall j \in \{1, 2\})(p_j = 1 \rightarrow x_j = 0)] \wedge [(\exists i \in \{1, 2, 3\})(p_i < 1) \rightarrow (\forall j \in \{1, 2, 3\})(p_j = 1 \rightarrow y_j = 0)]$.
In other words, if one of individuals 1 and 2 is negligent and the other nonnegligent, the entire accident loss resulting from interaction between 1 and 2 is to be borne by the negligent individual; and if one of individuals 1,2, and 3 is negligent then no nonnegligent individual is to bear any part of the accident loss resulting from interaction between individuals 1 and 3.

2 Sufficiency of NL-SJT for Efficiency of Liability Rules for Successive Joint Torts

Proposition 1 *If a liability rule for successive joint torts* $f : [0,1]^3 \mapsto [0,1]^5$ *satisfies the condition of negligence liability for successive joint torts then for any application* $< C_1, C_2, C_3, L_1, L_2, (c_1^*, c_2^*, c_3^*) \in M >$ *satisfying assumptions (A1)-(A4), i.e., belonging to* $\mathcal{A}$, (c_1^*, c_2^*, c_3^*) *is a Nash equilibrium.*

Proof: Let liability rule for successive joint torts f satisfy condition NL-SJT. Take any application $< C_1, C_2, C_3, L_1, L_2, (c_1^*, c_2^*, c_3^*) \in M >$ belonging to $\mathcal{A}$.
Denote $L_1(c_1^*, c_2^*)$ by L_1^*; $L_2(c_1^*, c_2^*, c_3^*)$ by L_2^*; $x_i(1,1)$ by $x_i^*, i = 1,2$; $y_i(1,1,1)$ by $y_i^*, i = 1,2,3$.
Suppose (c_1^*, c_2^*, c_3^*) is not a Nash equilibrium.
This implies:

$$(\exists c_1' \in C_1)[c_1' + x_1(p_1(c_1'), p_2(c_2^*))L_1(c_1', c_2^*) + y_1(p_1(c_1'), p_2(c_2^*), p_3(c_3^*))L_2(c_1', c_2^*, c_3^*) < c_1^* + x_1^*L_1^* + y_1^*L_2^*] \quad (P1.1)$$

$\vee$

$$(\exists c_2' \in C_2)[c_2' + x_2(p_1(c_1^*), p_2(c_2'))L_1(c_1^*, c_2') + y_2(p_1(c_1^*), p_2(c_2'), p_3(c_3^*))L_2(c_1^*, c_2', c_3^*) < c_2^* + x_2^*L_1^* + y_2^*L_2^*] \quad (P1.2)$$

$\vee$

$$(\exists c_3' \in C_3)[c_3' + y_3(p_1(c_1^*), p_2(c_2^*), p_3(c_3'))L_2(c_1^*, c_2^*, c_3') < c_3^* + y_3^*L_2^*]. \quad \text{(P1.3)}$$

First suppose (P1.1) holds.
$c_1' < c_1^* \wedge (P1.1) \to c_1' + L_1(c_1', c_2^*) + L_2(c_1', c_2^*, c_3^*) < c_1^* + x_1^*L_1^* + y_1^*L_2^*$, as $x_1(p_1(c_1'), p_2(c_2^*)) = 1 \wedge y_1(p_1(c_1'), p_2(c_2^*), p_3(c_3^*)) = 1$ by condition NL-SJT
$\to c_1' + L_1(c_1', c_2^*) + L_2(c_1', c_2^*, c_3^*) < c_1^* + L_1^* + L_2^*$, as $x_1^*, y_1^* \in [0,1]$ and $L_1^*, L_2^* \geq 0$
$\to c_1' + c_2^* + c_3^* + L_1(c_1', c_2^*) + L_2(c_1', c_2^*, c_3^*) < c_1^* + c_2^* + c_3^* + L_1^* + L_2^*$
$\to TSC(c_1', c_2^*, c_3^*) < TSC(c_1^*, c_2^*, c_3^*)$.
This is a contradiction as total social costs are minimum at (c_1^*, c_2^*, c_3^*). Therefore we conclude:

$c_1' < c_1^* \to$ (P1.1) cannot hold. (P1.4)

Next Consider $c_1' > c_1^*$.
$c_1' > c_1^* \to x_1(p_1(c_1'), p_2(c_2^*)) = x_1^* \wedge y_1(p_1(c_1'), p_2(c_2^*), p_3(c_3^*)) = y_1^*$.

$$c_1' > c_1^* \wedge (P1.1) \to c_1' + x_1^*L_1(c_1', c_2^*) + y_1^*L_2(c_1', c_2^*, c_3^*) < c_1^* + x_1^*L_1^* + y_1^*L_2^*. \quad \text{(P1.5)}$$

$x_1^* \geq y_1^* \vee x_1^* < y_1^*$.

First suppose $x_1^* \geq y_1^*$.
$x_1^* \geq y_1^* \wedge c_1' > c_1^* \wedge (P1.5) \to (1 - x_1^*)c_1' + x_1^*(c_1' + L_1(c_1', c_2^*) + L_2(c_1', c_2^*, c_3^*)) - (x_1^* - y_1^*)L_2(c_1', c_2^*, c_3^*) < (1 - x_1^*)c_1^* + x_1^*(c_1^* + L_1^* + L_2^*) - (x_1^* - y_1^*)L_2^*$.

By adding $x_1^*(c_2^* + c_3^*)$ to both sides we obtain:
$x_1^* \geq y_1^* \wedge c_1' > c_1^* \wedge (P1.5) \rightarrow (1 - x_1^*)c_1' + x_1^*(c_1' + c_2^* + c_3^* + L_1(c_1', c_2^*) + L_2(c_1', c_2^*, c_3^*)) - (x_1^* - y_1^*)L_2(c_1', c_2^*, c_3^*) < (1 - x_1^*)c_1^* + x_1^*(c_1^* + c_2^* + c_3^* + L_1^* + L_2^*) - (x_1^* - y_1^*)L_2^*$
$\rightarrow (1-x_1^*)c_1' + x_1^*(TSC(c_1', c_2^*, c_3^*) - TSC(c_1^*, c_2^*, c_3^*)) + (x_1^* - y_1^*)(L_2^* - L_2(c_1', c_2^*, c_3^*)) < (1-x_1^*)c_1^*$
$\rightarrow (1 - x_1^*)c_1' < (1 - x_1^*)c_1^*$, as $TSC(c_1', c_2^*, c_3^*) - TSC(c_1^*, c_2^*, c_3^*) \geq 0$ in view of the fact that TSC is minimized at (c_1^*, c_2^*, c_3^*) and $L_2^* - L_2(c_1', c_2^*, c_3^*) \geq 0$ by assumption A(3). (P1.6)
$(1 - x_1^*) > 0 \wedge (P1.6) \rightarrow c_1' < c_1^*$, a contradiction as by assumption $c_1' > c_1^*$. (P1.7)
$(1 - x_1^*) = 0 \wedge (P1.6) \rightarrow 0 < 0$, a contradiction. (P1.8)
From (P1.7) and (P1.8), it follows that if $x_1^* \geq y_1^* \wedge c_1' > c_1^*$ then (P1.1) cannot hold. (P1.9)
Analogously it can be shown that if $x_1^* < y_1^* \wedge c_1' > c_1^*$ then (P1.1) cannot hold. (P1.10)
(P1.9) and (P1.10) establish that if $c_1' > c_1^*$ then (P1.1) cannot hold. (P1.11)
(P1.4) and (P1.11) establish that (P1.1) cannot hold. (P1.12)

The proof of that (P1.2) cannot hold is similar to the proof that (P1.1) cannot hold. (P1.13)

Next suppose that (P1.3) holds.
$c_3' < c_3^* \wedge (P1.3) \rightarrow c_3' + L_2(c_1^*, c_2^*, c_3') < c_3^* + y_3^* L_2^*$, as $y_3(p_1(c_1^*), p_2(c_2^*), p_3(c_3')) = 1$ by condition NL-SJT
$\rightarrow c_3' + L_2(c_1^*, c_2^*, c_3') < c_3^* + L_2^*$, as $y_3^* \in [0, 1]$.
By adding $c_1^* + c_2^* + L_1^*$ to both sides we obtain:
$c_1^* + c_2^* + c_3' + L_1^* + L_2(c_1^*, c_2^*, c_3') < c_1^* + c_2^* + c_3^* + L_1^* + L_2^*$
$\rightarrow TSC(c_1^*, c_2^*, c_3') < TSC(c_1^*, c_2^*, c_3^*)$, a contradiction as TSC is minimized at (c_1^*, c_2^*, c_3^*).
Therefore it follows that if $c_3' < c_3^*$ then (P1.3) cannot hold. (P1.14)
$c_3' > c_3^* \wedge (P1.3) \rightarrow c_3' + y_3^* L_2(c_1^*, c_2^*, c_3') < c_3^* + y_3^* L_2^*$, as $y_3(p_1(c_1^*), p_2(c_2^*), p_3(c_3')) = y_3^*$.
By adding $y_3^*[c_1^* + c_2^* + L_1^*]$ to both sides, we obtain:
$(1 - y_3^*)c_3' + y_3^*(c_1^* + c_2^* + c_3' + L_1^* + L_2(c_1^*, c_2^*, c_3')) < (1 - y_3^*)c_3^* + y_3^*(c_1^* + c_2^* + c_3^* + L_1^* + L_2^*)$
$\rightarrow (1 - y_3^*)c_3' + y_3^*(TSC(c_1^*, c_2^*, c_3')) < (1 - y_3^*)c_3^* + y_3^*(TSC(c_1^*, c_2^*, c_3^*))$
$\rightarrow (1 - y_3^*)c_3' < (1 - y_3^*)c_3^*$. (P1.15)
If $(1-y_3^*) > 0$, then $(P1.15) \rightarrow c_3' < c_3^*$, a contradiction as $c_3' > c_3^*$ by assumption. (P1.16)
If $(1 - y_3^*) = 0$, then $(P1.15) \rightarrow 0 < 0$, a contradiction. (P1.17)
(P1.16) and (P1.17) establish that if $c_3' > c_3^*$ then (P1.3) cannot hold. (P1.18)
(P1.14) and (P1.18) establish that (P1.3) cannot hold. (P1.19)

(P1.12), (P1.13), and (P1.19) establish that (c_1^*, c_2^*, c_3^*) is a Nash equilibrium.

□

Proposition 2 *If a liability rule for successive joint torts $f : [0,1]^3 \mapsto [0,1]^5$ satisfies the condition of negligence liability for successive joint torts then for any application* <

$C_1, C_2, C_3, L_1, L_2, (c_1^*, c_2^*, c_3^*) \in M >$ *satisfying assumptions (A1)-(A4), i.e., belonging to* $\mathcal{A}$ *the following holds:*
$(\forall(\overline{c}_1, \overline{c}_2, \overline{c}_3) \in C_1 \times C_2 \times C_3)[(\overline{c}_1, \overline{c}_2, \overline{c}_3)$ *is a Nash equilibrium* $\rightarrow$ $(\overline{c}_1, \overline{c}_2, \overline{c}_3) \in M]$.

Proof: Let liability rule for successive joint torts f satisfy NL-SJT. Take any application $< C_1, C_2, C_3, L_1, L_2, (c_1^*, c_2^*, c_3^*) \in M >$ belonging to $\mathcal{A}$.
Denote $L_1(\overline{c}_1, \overline{c}_2)$ by $\overline{L}_1$; $L_2(\overline{c}_1, \overline{c}_2, \overline{c}_3)$ by $\overline{L}_2$; $L_1(c_1^*, c_2^*)$ by L_1^*; $L_2(c_1^*, c_2^*, c_3^*)$ by L_2^*; $x_i(p_1(\overline{c}_1), p_2(\overline{c}_2))$ by $\overline{x}_i, i = 1, 2$; $y_i(p_1(\overline{c}_1), p_2(\overline{c}_2), p_3(\overline{c}_3))$ by $\overline{y}_i, i = 1, 2, 3,$; $x_i(p_1(c_1^*), p_2(c_2^*))$ by $x_i^*, i = 1, 2$; and $y_i(p_1(c_1^*), p_2(c_2^*), p_3(c_3^*))$ by $y_i^*, i = 1, 2, 3$.
Let $(\overline{c}_1, \overline{c}_2, \overline{c}_3)$ be a Nash equilibrium.
$(\overline{c}_1, \overline{c}_2, \overline{c}_3)$ is a Nash equilibrium $\rightarrow$
$(\forall c_1 \in C_1)[\overline{c_1} + \overline{x}_1\overline{L}_1 + \overline{y}_1\overline{L}_2 \leq c_1 + x_1(p_1(c_1), p_2(\overline{c}_2))L_1(c_1, \overline{c}_2) + y_1(p_1(c_1), p_2(\overline{c}_2), p_3(\overline{c}_3))L_2(c_1, \overline{c}_2, \overline{c}_3)]$ (P2.1)
$\wedge$
$(\forall c_2 \in C_2)[\overline{c_2} + \overline{x}_2\overline{L}_1 + \overline{y}_2\overline{L}_2 \leq c_2 + x_2(p_1(\overline{c}_1), p_2(c_2))L_1(\overline{c}_1, c_2) + y_2(p_1(\overline{c}_1), p_2(c_2), p_3(\overline{c}_3))L_2(\overline{c}_1, c_2, \overline{c}_3)]$ (P2.2)
$\wedge$
$(\forall c_3 \in C_3)[\overline{c_3} + \overline{y}_3\overline{L}_2 \leq c_3 + y_3(p_1(\overline{c}_1), p_2(\overline{c}_2), p_3(c_3))L_2(\overline{c}_1, \overline{c}_2, c_3)]$. (P2.3)
(P2.1), (P2.2), and (P2.3) imply respectively:
$\overline{c}_1 + \overline{x}_1\overline{L}_1 + \overline{y}_1\overline{L}_2 \leq c_1^* + x_1(p_1(c_1^*), p_2(\overline{c}_2))L_1(c_1^*, \overline{c}_2) + y_1(p_1(c_1^*), p_2(\overline{c}_2), p_3(\overline{c}_3))L_2(c_1^*, \overline{c}_2, \overline{c}_3)$. (P2.4)
$\overline{c}_2 + \overline{x}_2\overline{L}_1 + \overline{y}_2\overline{L}_2 \leq c_2^* + x_2(p_1(\overline{c}_1), p_2(c_2^*))L_1(\overline{c}_1, c_2^*) + y_2(p_1(\overline{c}_1), p_2(c_2^*), p_3(\overline{c}_3))L_2(\overline{c}_1, c_2^*, \overline{c}_3)$. (P2.5)
$\overline{c}_3 + \overline{y}_3\overline{L}_2 \leq c_3^* + y_3(p_1(\overline{c}_1), p_2(\overline{c}_2), p_3(c_3^*))L_2(\overline{c}_1, \overline{c}_2, c_3^*)$. (P2.6)
Adding inequalities (P2.4), (P2.5) and (P2.6) we obtain:
$\overline{c}_1 + \overline{c}_2 + \overline{c}_3 + \overline{L}_1 + \overline{L}_2 \leq c_1^* + c_2^* + c_3^* + x_1(p_1(c_1^*), p_2(\overline{c}_2))L_1(c_1^*, \overline{c}_2) + x_2(p_1(\overline{c}_1), p_2(c_2^*))L_1(\overline{c}_1, c_2^*) +$
$y_1(p_1(c_1^*), p_2(\overline{c}_2), p_3(\overline{c}_3))L_2(c_1^*, \overline{c}_2, \overline{c}_3) + y_2(p_1(\overline{c}_1), p_2(c_2^*), p_3(\overline{c}_3))L_2(\overline{c}_1, c_2^*, \overline{c}_3)$
$+ y_3(p_1(\overline{c}_1), p_2(\overline{c}_2), p_3(c_3^*))L_2(\overline{c}_1, \overline{c}_2, c_3^*)$. (P2.7)

By the definition of nonnegligence functions we have:
$\overline{c}_1 \geq c_1^* \rightarrow x_2(p_1(\overline{c}_1), p_2(c_2^*)) = x_2^*$
$\overline{c}_2 \geq c_2^* \rightarrow x_1(p_1(c_1^*), p_2(\overline{c}_2)) = x_1^*$
$\overline{c}_1 \geq c_1^* \wedge \overline{c}_2 \geq c_2^* \rightarrow y_3(p_1(\overline{c}_1), p_2(\overline{c}_2), p_3(c_3^*)) = y_3^*$
$\overline{c}_1 \geq c_1^* \wedge \overline{c}_3 \geq c_3^* \rightarrow y_2(p_1(\overline{c}_1), p_2(c_2^*), p_3(\overline{c}_3)) = y_2^*$
$\overline{c}_2 \geq c_2^* \wedge \overline{c}_3 \geq c_3^* \rightarrow y_1(p_1(c_1^*), p_2(\overline{c}_2), p_3(\overline{c}_3)) = y_1^*$.

By condition NL-SJT we obtain:
$\overline{c}_1 < c_1^* \rightarrow x_2(p_1(\overline{c}_1), p_2(c_2^*)) = 0 \wedge y_2(p_1(\overline{c}_1), p_2(c_2^*), p_3(\overline{c}_3)) = 0 \wedge y_3(p_1(\overline{c}_1), p_2(\overline{c}_2), p_3(c_3^*)) = 0$
$\overline{c}_2 < c_2^* \rightarrow x_1(p_1(c_1^*), p_2(\overline{c}_2)) = 0 \wedge y_1(p_1(c_1^*), p_2(\overline{c}_2), p_3(\overline{c}_3)) = 0 \wedge y_3(p_1(\overline{c}_1), p_2(\overline{c}_2), p_3(c_3^*)) = 0$
$\overline{c}_3 < c_3^* \rightarrow y_1(p_1(c_1^*), p_2(\overline{c}_2), p_3(\overline{c}_3)) = 0 \wedge y_2(p_1(\overline{c}_1), p_2(c_2^*), p_3(\overline{c}_3)) = 0$.

By assumptions (A2) and (A3), we have:
$\overline{c}_1 \geq c_1^* \rightarrow L_1(\overline{c}_1, c_2^*) \leq L_1^*$
$\overline{c}_2 \geq c_2^* \rightarrow L_1(c_1^*, \overline{c}_2) \leq L_1^*$
$\overline{c}_1 \geq c_1^* \wedge \overline{c}_2 \geq c_2^* \rightarrow L_2(\overline{c}_1, \overline{c}_2, c_3^*) \leq L_2^*$
$\overline{c}_1 \geq c_1^* \wedge \overline{c}_3 \geq c_3^* \rightarrow L_2(\overline{c}_1, c_2^*, \overline{c}_3) \leq L_2^*$
$\overline{c}_2 \geq c_2^* \wedge \overline{c}_3 \geq c_3^* \rightarrow L_2(c_1^*, \overline{c}_2, \overline{c}_3) \leq L_2^*$.

In view of the above we obtain:

$$\overline{c}_1 \geq c_1^* \wedge \overline{c}_2 \geq c_2^* \wedge \overline{c}_3 \geq c_3^* \wedge (P2.7) \rightarrow \overline{c}_1 + \overline{c}_2 + \overline{c}_3 + \overline{L}_1 + \overline{L}_2 \leq c_1^* + c_2^* + c_3^* + x_1^* L_1(c_1^*, \overline{c}_2) + x_2^* L_1(\overline{c}_1, c_2^*) + y_1^* L_2(c_1^*, \overline{c}_2, \overline{c}_3) + y_2^* L_2(\overline{c}_1, c_2^*, \overline{c}_3) + y_3^* L_2(\overline{c}_1, \overline{c}_2, c_3^*) \leq c_1^* + c_2^* + c_3^* + x_1^* L_1^* + x_2^* L_1^* + y_1^* L_2^* + y_2^* L_2^* + y_3^* L_2^* = c_1^* + c_2^* + c_3^* + L_1^* + L_2^* \quad \text{(P2.8)}$$

$$\overline{c}_1 < c_1^* \wedge \overline{c}_2 \geq c_2^* \wedge \overline{c}_3 \geq c_3^* \wedge (P2.7) \rightarrow \overline{c}_1 + \overline{c}_2 + \overline{c}_3 + \overline{L}_1 + \overline{L}_2 \leq c_1^* + c_2^* + c_3^* + x_1^* L_1(c_1^*, \overline{c}_2) + y_1^* L_2(c_1^*, \overline{c}_2, \overline{c}_3) \leq c_1^* + c_2^* + c_3^* + x_1^* L_1^* + y_1^* L_2^* \leq c_1^* + c_2^* + c_3^* + L_1^* + L_2^* \quad \text{(P2.9)}$$

$$\overline{c}_1 \geq c_1^* \wedge \overline{c}_2 < c_2^* \wedge \overline{c}_3 \geq c_3^* \wedge (P2.7) \rightarrow \overline{c}_1 + \overline{c}_2 + \overline{c}_3 + \overline{L}_1 + \overline{L}_2 \leq c_1^* + c_2^* + c_3^* + x_2^* L_1(\overline{c}_1, c_2^*) + y_2^* L_2(\overline{c}_1, c_2^*, \overline{c}_3) \leq c_1^* + c_2^* + c_3^* + x_2^* L_1^* + y_2^* L_2^* \leq c_1^* + c_2^* + c_3^* + L_1^* + L_2^* \quad \text{(P2.10)}$$

$$\overline{c}_1 \geq c_1^* \wedge \overline{c}_2 \geq c_2^* \wedge \overline{c}_3 < c_3^* \wedge (P2.7) \rightarrow \overline{c}_1 + \overline{c}_2 + \overline{c}_3 + \overline{L}_1 + \overline{L}_2 \leq c_1^* + c_2^* + c_3^* + x_1^* L_1(c_1^*, \overline{c}_2) + x_2^* L_1(\overline{c}_1, c_2^*) + y_3^* L_2(\overline{c}_1, \overline{c}_2, c_3^*) \leq c_1^* + c_2^* + c_3^* + x_1^* L_1^* + x_2^* L_1^* + y_3^* L_2^* \leq c_1^* + c_2^* + c_3^* + L_1^* + L_2^* \quad \text{(P2.11)}$$

$$\overline{c}_1 < c_1^* \wedge \overline{c}_2 < c_2^* \wedge \overline{c}_3 \geq c_3^* \wedge (P2.7) \rightarrow \overline{c}_1 + \overline{c}_2 + \overline{c}_3 + \overline{L}_1 + \overline{L}_2 \leq c_1^* + c_2^* + c_3^* \leq c_1^* + c_2^* + c_3^* + L_1^* + L_2^* \quad \text{(P2.12)}$$

$$\overline{c}_1 < c_1^* \wedge \overline{c}_2 \geq c_2^* \wedge \overline{c}_3 < c_3^* \wedge (P2.7) \rightarrow \overline{c}_1 + \overline{c}_2 + \overline{c}_3 + \overline{L}_1 + \overline{L}_2 \leq c_1^* + c_2^* + c_3^* + x_1^* L_1(c_1^*, \overline{c}_2) \leq c_1^* + c_2^* + c_3^* + x_1^* L_1^* \leq c_1^* + c_2^* + c_3^* + L_1^* \leq c_1^* + c_2^* + c_3^* + L_1^* + L_2^* \quad \text{(P2.13)}$$

$$\overline{c}_1 \geq c_1^* \wedge \overline{c}_2 < c_2^* \wedge \overline{c}_3 < c_3^* \wedge (P2.7) \rightarrow \overline{c}_1 + \overline{c}_2 + \overline{c}_3 + \overline{L}_1 + \overline{L}_2 \leq c_1^* + c_2^* + c_3^* + x_2^* L_1(\overline{c}_1, c_2^*) \leq c_1^* + c_2^* + c_3^* + x_2^* L_1^* \leq c_1^* + c_2^* + c_3^* + L_1^* \leq c_1^* + c_2^* + c_3^* + L_1^* + L_2^* \quad \text{(P2.14)}$$

$$\overline{c}_1 < c_1^* \wedge \overline{c}_2 < c_2^* \wedge \overline{c}_3 < c_3^* \wedge (P2.7) \rightarrow \overline{c}_1 + \overline{c}_2 + \overline{c}_3 + \overline{L}_1 + \overline{L}_2 \leq c_1^* + c_2^* + c_3^* \leq c_1^* + c_2^* + c_3^* + L_1^* + L_2^* \quad \text{(P2.15)}$$

(P2.8)-(P2.15) establish that: $TSC(\overline{c}_1, \overline{c}_2, \overline{c}_3) \leq TSC(c_1^*, c_2^*, c_3^*)$. As TSC is minimized at (c_1^*, c_2^*, c_3^*), it follows that $TSC(\overline{c}_1, \overline{c}_2, \overline{c}_3) = TSC(c_1^*, c_2^*, c_3^*)$; and that $(\overline{c}_1, \overline{c}_2, \overline{c}_3) \in M$.

□

Combining Propositions 1 and 2 we obtain:

Theorem 1 *If a liability rule for successive joint torts $f : [0, 1]^3 \mapsto [0, 1]^5$ satisfies the condition of negligence liability for successive joint torts (NL-SJT) then it is efficient for* *all applications belonging to $\mathcal{A}$.*

The following corollary follows immediately from the above Theorem.

Corrolary 1 *If a simple liability rule for successive joint torts $f : [0,1]^3 \mapsto [0,1]^5$ satisfies the condition of negligence liability for successive joint torts (NL-SJT) then it is efficient for all applications belonging to $\mathcal{A}$.*

Remark 1 *As the Landes-Posner rule satisfies the condition of NL-SJT, its efficiency follows immediately from Theorem 1.*

$\Diamond$

3 Characterization of Efficient Simple Liability Rules for Successive Joint Torts

Proposition 3 *If a simple liability rule for successive joint torts $f : \{0,1\}^3 \mapsto [0,1]^5$ is efficient for every application $< C_1, C_2, C_3, L_1, L_2, (c_1^*, c_2^*, c_3^*) \in M >$ belonging to $\mathcal{A}$, then the following holds:* $[(\exists i \in \{1,2\})(p_i = 0) \rightarrow (\forall j \in \{1,2\})(p_j = 1 \rightarrow x_j = 0)]$.

Proof: Suppose f violates $[(\exists i \in \{1,2\})(p_i = 0) \rightarrow (\forall j \in \{1,2\})(p_j = 1 \rightarrow x_j = 0)]$, i.e., we have: $[(\exists i, j \in \{1,2\})(p_i = 0 \wedge p_j = 1 \wedge x_j \neq 0)]$. Without any loss of generality, assume $i = 2 \wedge j = 1$. So we have: $0 \leq x_2(1,0) < 1$. Designate $x_2(1,0)$ by x_2^0.

Choose $t > 0$; and let $0 \leq x_2^0 t < r < t$.
As $t > 0$ and $r - x_2^0 t > 0$, there exists a positive integer n such that:
$\frac{1}{n} < \frac{r - x_2^0 t}{t}$.
Let:
$\frac{1}{n} = \mu$
$\alpha, \beta, \epsilon_1, \epsilon_2, \epsilon_3 > 0$ and
$\epsilon_1 + \epsilon_2 > \alpha$.
Consider the application belonging to $\mathcal{A}$ given by:
$C_1 = \{0, \alpha\}; C_2 = \{0, r\}; C_3 = \{0, \beta\}$.
Let L_1 be as given in the following array:

$L_1(c_1, c_2)$

	$c_2 = 0$	$c_2 = r$
$c_1 = 0$	$\epsilon_1 + t$	ϵ_1
$c_1 = \alpha$	t	0

Let L_2 be specified as given in the following two arrays:

$L_2(c_1, c_2, 0)$

	$c_2 = 0$	$c_2 = r$
$c_1 = 0$	$\epsilon_2 + \mu t + \beta + \epsilon_3$	$\epsilon_2 + \beta + \epsilon_3$
$c_1 = \alpha$	$\mu t + \beta + \epsilon_3$	$\beta + \epsilon_3$

$L_2(c_1, c_2, \beta)$

	$c_2 = 0$	$c_2 = r$
$c_1 = 0$	$\epsilon_2 + \mu t$	ϵ_2
$c_1 = \alpha$	μt	0

As we have $(\forall (c_1, c_2, c_3), (c'_1, c'_2, c'_3))[[c_1 = 0 \wedge c'_1 = \alpha \wedge c_2 = c'_2 \wedge c_3 = c'_3 \rightarrow L_1(c_1, c_2) - L_1(c'_1, c'_2) = \epsilon_1 \wedge L_2(c_1, c_2, c_3) - L_2(c'_1, c'_2, c'_3) = \epsilon_2] \wedge [c_1 = c'_1 \wedge c_2 = 0 \wedge c'_2 = r \wedge c_3 = c'_3 \rightarrow L_1(c_1, c_2) - L_1(c'_1, c'_2) = t \wedge L_2(c_1, c_2, c_3) - L_2(c'_1, c'_2, c'_3) = \mu t] \wedge [c_1 = c'_1 \wedge c_2 = c'_2 \wedge c_3 = 0 \wedge c'_3 = \beta \rightarrow L_2(c_1, c_2, c_3) - L_2(c'_1, c'_2, c'_3) = \beta + \epsilon_3]]$, it follows that TSC is uniquely minimized at (α, r, β).

Let $(\alpha, r, \beta) = (c^*_1, c^*_2, c^*_3)$.

Now, $EC_2(\alpha, r, \beta) = r$.
$EC_2(\alpha, 0, \beta) = x^0_2 t + y_2(1, 0, 1)\mu t$.
$EC_2(\alpha, r, \beta) - EC_2(\alpha, 0, \beta) = r - x^0_2 t - y_2(1, 0, 1)\mu t$
$\geq (r - x^0_2 t) - \mu t$
> 0.
Thus the unique TSC-minimizing configuration of care costs is not a Nash equilibrium. Thus f is inefficient for the application belonging to $\mathcal{A}$ considered herein.
Therefore it follows that if f violates the condition $[(\exists i \in \{1, 2\})(p_i = 0) \rightarrow (\forall j \in \{1, 2\})(p_j = 1 \rightarrow x_j = 0)]$ then it is not efficient for all applications belonging to $\mathcal{A}$.

□

Proposition 4 *If a simple liability rule for successive joint torts* $f : \{0, 1\}^3 \mapsto [0, 1]^5$ *satisfying the condition* $[(\exists i \in \{1, 2\})(p_i = 0) \rightarrow (\forall j \in \{1, 2\})(p_j = 1 \rightarrow x_j = 0)]$ *is efficient for every application* $< C_1, C_2, C_3, L_1, L_2, (c^*_1, c^*_2, c^*_3) \in M >$ *belonging to* $\mathcal{A}$, *then the following holds:* $[(\exists i \in \{1, 2, 3\})(p_i = 0) \rightarrow (\forall j \in \{1, 2, 3\})(p_j = 1 \rightarrow y_j = 0)]$.

Proof: Let f be a simple liability rule for successive joint torts $f : \{0,1\}^3 \mapsto [0,1]^5$ satisfying the condition $[(\exists i \in \{1,2\})(p_i = 0) \rightarrow (\forall j \in \{1,2\})(p_j = 1 \rightarrow x_j = 0)]$.
Suppose f violates $[(\exists i \in \{1,2,3\})(p_i = 0) \rightarrow (\forall j \in \{1,2,3\})(p_j = 1 \rightarrow y_j = 0)]$, i.e., we have: $\{i \in \{1,2,3\} \mid p_i = 0\} = N' \neq \emptyset \wedge \sum_{i \in N'} y_i \neq 1$. Among all such N', $\{i \in \{1,2,3\} \mid p_i = 0\} = N' \neq \emptyset \wedge \sum_{i \in N'} y_i \neq 1$, choose the smallest one or one of the smallest ones, and designate it by N^0. There are six distinct cases to be considered:
(i) $N^0 = \{1\}$
(ii) $N^0 = \{2\}$
(iii) $N^0 = \{3\}$
(iv) $N^0 = \{1,2\}$
(v) $N^0 = \{1,3\}$
(vi) $N^0 = \{2,3\}$.
As conceptually cases (i) and (ii) are similar, and cases (v) and (vi) are similar, it suffices to consider only four cases.

Case: $N^0 = \{2\}$

Designate $y_2(1,0,1)$ by y_2^0. By assumption, $y_2^0 < 1$.
Choose $t > 0$; and let $0 \leq y_2^0 t < r < t$.
As $t > 0$ and $r - y_2^0 t > 0$, there exists a positive integer n such that:
$\frac{1}{n} < \frac{r - y_2^0 t}{t}$.
Let:
$\frac{1}{n} = \mu$
$\alpha, \beta, \epsilon_1, \epsilon_2, \epsilon_3 > 0$.
$\epsilon_1 + \epsilon_2 > \alpha$.
Consider the application belonging to $\mathcal{A}$ given by:
$C_1 = \{0, \alpha\}; C_2 = \{0, r\}; C_3 = \{0, \beta\}$.
Let L_1 be as given in the following array:

$L_1(c_1, c_2)$

	$c_2 = 0$	$c_2 = r$
$c_1 = 0$	$\epsilon_1 + \mu t$	ϵ_1
$c_1 = \alpha$	μt	0

Let L_2 be specified as given in the following two arrays:

$L_2(c_1, c_2, 0)$

	$c_2 = 0$	$c_2 = r$
$c_1 = 0$	$\epsilon_2 + t + \beta + \epsilon_3$	$\epsilon_2 + \beta + \epsilon_3$
$c_1 = \alpha$	$t + \beta + \epsilon_3$	$\beta + \epsilon_3$

$L_2(c_1, c_2, \beta)$

	$c_2 = 0$	$c_2 = r$
$c_1 = 0$	$\epsilon_2 + t$	ϵ_2
$c_1 = \alpha$	t	0

As we have $(\forall(c_1, c_2, c_3), (c_1', c_2', c_3'))[[c_1 = 0 \wedge c_1' = \alpha \wedge c_2 = c_2' \wedge c_3 = c_3' \rightarrow L_1(c_1, c_2) - L_1(c_1', c_2') = \epsilon_1 \wedge L_2(c_1, c_2, c_3) - L_2(c_1', c_2', c_3') = \epsilon_2] \wedge [c_1 = c_1' \wedge c_2 = 0 \wedge c_2' = r \wedge c_3 = c_3' \rightarrow L_1(c_1, c_2) - L_1(c_1', c_2') = \mu t \wedge L_2(c_1, c_2, c_3) - L_2(c_1', c_2', c_3') = t] \wedge [c_1 = c_1' \wedge c_2 = c_2' \wedge c_3 = 0 \wedge c_3' = \beta \rightarrow L_2(c_1, c_2, c_3) - L_2(c_1', c_2', c_3') = \beta + \epsilon_3]]$, it follows that TSC is uniquely minimized at (α, r, β).

Let $(\alpha, r, \beta) = (c_1^*, c_2^*, c_3^*)$.

Now, $EC_2(\alpha, r, \beta) = r$.
$EC_2(\alpha, 0, \beta) = x_2(1, 0)\mu t + y_2(1, 0, 1)t = \mu t + y_2^0 t$, as $x_2(1, 0) = 1$, in view of the condition $[(\exists i \in \{1, 2\})(p_i = 0) \rightarrow (\forall j \in \{1, 2\})(p_j = 1 \rightarrow x_j = 0)]$.
$EC_2(\alpha, r, \beta) - EC_2(\alpha, 0, \beta) = r - \mu t - y_2^0 t$
$= (r - y_2^0 t) - \mu t$
> 0.
Thus the unique TSC-minimizing configuration of care costs is not a Nash equilibrium. Therefore f is inefficient for the application belonging to $\mathcal{A}$ considered herein.

Case: $N^0 = \{3\}$

Designate $y_3(1, 1, 0)$ by y_3^0. By assumption, $y_3^0 < 1$.
Choose $t > 0$; and let $0 \leq y_3^0 t < r < t$.
Let:
$\alpha, \beta, \epsilon_1, \epsilon_2, \epsilon_3, \epsilon_4 > 0$
$\epsilon_1 + \epsilon_2 > \alpha$
$\epsilon_3 + \epsilon_4 > \beta$.

Consider the application belonging to $\mathcal{A}$ given by:
$C_1 = \{0, \alpha\}; C_2 = \{0, \beta\}; C_3 = \{0, r\}$.

Let L_1 be as given in the following array:

$L_1(c_1, c_2)$

	$c_2 = 0$	$c_2 = \beta$
$c_1 = 0$	$\epsilon_1 + \epsilon_3$	ϵ_1
$c_1 = \alpha$	ϵ_3	0

Let L_2 be specified as given in the following two arrays:

$L_2(c_1, c_2, 0)$

	$c_2 = 0$	$c_2 = \beta$
$c_1 = 0$	$\epsilon_2 + \epsilon_4 + t$	$\epsilon_2 + t$
$c_1 = \alpha$	$\epsilon_4 + t$	t

$L_2(c_1, c_2, r)$

	$c_2 = 0$	$c_2 = \beta$
$c_1 = 0$	$\epsilon_2 + \epsilon_4$	ϵ_2
$c_1 = \alpha$	ϵ_4	0

As we have $(\forall(c_1, c_2, c_3), (c_1', c_2', c_3'))[[c_1 = 0 \wedge c_1' = \alpha \wedge c_2 = c_2' \wedge c_3 = c_3' \rightarrow L_1(c_1, c_2) - L_1(c_1', c_2') = \epsilon_1 \wedge L_2(c_1, c_2, c_3) - L_2(c_1', c_2', c_3') = \epsilon_2] \wedge [c_1 = c_1' \wedge c_2 = 0 \wedge c_2' = \beta \wedge c_3 = c_3' \rightarrow L_1(c_1, c_2) - L_1(c_1', c_2') = \epsilon_3 \wedge L_2(c_1, c_2, c_3) - L_2(c_1', c_2', c_3') = \epsilon_4] \wedge [c_1 = c_1' \wedge c_2 = c_2' \wedge c_3 = 0 \wedge c_3' = r \rightarrow L_2(c_1, c_2, c_3) - L_2(c_1', c_2', c_3') = t]]$, it follows that TSC is uniquely minimized at (α, β, r).

Let $(\alpha, \beta, r) = (c_1^*, c_2^*, c_3^*)$.

Now, $EC_3(\alpha, \beta, r) = r$.
$EC_3(\alpha, \beta, 0) = y_3(1, 1, 0)t = y_3^0 t$.
$EC_3(\alpha, \beta, r) - EC_3(\alpha, \beta, 0) = r - y_3^0 t$
> 0.
Thus the unique TSC-minimizing configuration of care costs is not a Nash equilibrium. Therefore f is inefficient for the application belonging to $\mathcal{A}$ considered herein.

Case: $N^0 = \{1, 2\}$

Designate $y_1(0,0,1)$ by y_1^0 and $y_2(0,0,1)$ by y_2^0. By assumption, $y_1^0 + y_2^0 < 1$.
Let $t > 0$.
If $y_i^0 > 0, i = 1,2$, then choose r_i such that: $0 < y_i^0 t < r_i < \frac{y_i^0}{y_1^0+y_2^0}t$.
If $y_i^0 = 0, i = 1,2$, then choose $r_i = 0$.
Thus we have: $0 \leq r_1 + r_2 < t$.
Choose v such that: $r_1 + r_2 < v < t$.
Let: $\delta = t - v$; $\epsilon = v - (r_1 + r_2)$; and $0 < \beta < 1$.
Let: $0 < \alpha < min\{r_1 + \frac{\epsilon}{2} - ty_1^0, r_2 + \frac{\epsilon}{2} - ty_2^0\}$.

Consider the application given by:
$C_1 = \{0, r_1 + \frac{\epsilon}{2}\}; C_2 = \{0, r_2 + \frac{\epsilon}{2}\}; C_3 = \{0, \alpha\}$.
Let L_1 be as given in the following array:

$L_1(c_1, c_2)$

	$c_2 = 0$	$c_2 = r_2 + \frac{\epsilon}{2}$
$c_1 = 0$	$\frac{\alpha\beta}{2}$	$\frac{\alpha\beta}{4}$
$c_1 = r_1 + \frac{\epsilon}{2}$	$\frac{\alpha\beta}{4}$	0

Let L_2 be specified as given in the following two arrays:

$L_2(c_1, c_2, 0)$

	$c_2 = 0$	$c_2 = r_2 + \frac{\epsilon}{2}$
$c_1 = 0$	$r_1 + r_2 + \epsilon + \delta + \frac{\alpha\beta}{2}$	$r_1 + \frac{\epsilon}{2} + \frac{\delta}{2} + \frac{\alpha\beta}{2}$
$c_1 = r_1 + \frac{\epsilon}{2}$	$r_2 + \frac{\epsilon}{2} + \frac{\delta}{2} + \frac{\alpha\beta}{2}$	$\frac{\alpha\beta}{2}$

$L_2(c_1, c_2, \alpha)$

	$c_2 = 0$	$c_2 = r_2 + \frac{\epsilon}{2}$
$c_1 = 0$	$r_1 + r_2 + \epsilon + \delta$	$r_1 + \frac{\epsilon}{2} + \frac{\delta}{2}$
$c_1 = r_1 + \frac{\epsilon}{2}$	$r_2 + \frac{\epsilon}{2} + \frac{\delta}{2}$	0

As we have $(\forall(c_1, c_2, c_3), (c_1', c_2', c_3'))[[c_1 = 0 \wedge c_1' = r_1 + \frac{\epsilon}{2} \wedge c_2 = c_2' \wedge c_3 = c_3' \rightarrow L_1(c_1, c_2) - L_1(c_1', c_2') = \frac{\alpha\beta}{4} \wedge L_2(c_1, c_2, c_3) - L_2(c_1', c_2', c_3') = r_1 + \frac{\epsilon}{2} + \frac{\delta}{2}] \wedge [c_1 = c_1' \wedge c_2 = 0 \wedge c_2' = r_2 + \frac{\epsilon}{2} \wedge c_3 = c_3' \rightarrow L_1(c_1, c_2) - L_1(c_1', c_2') = \frac{\alpha\beta}{4} \wedge L_2(c_1, c_2, c_3) - L_2(c_1', c_2', c_3') = r_2 + \frac{\epsilon}{2} + \frac{\delta}{2}] \wedge [c_1 = c_1' \wedge c_2 = c_2' \wedge c_3 = 0 \wedge c_3' = \alpha \rightarrow L_2(c_1, c_2, c_3) - L_2(c_1', c_2', c_3') = \frac{\alpha\beta}{2}]]$, it follows that TSC is uniquely minimized at $(r_1 + \frac{\epsilon}{2}, r_2 + \frac{\epsilon}{2}, 0)$.

We have:
$EC_1(0,0,0) = x_1(0,0)\frac{\alpha\beta}{2} + y_1(0,0,1)(r_1 + r_2 + \epsilon + \delta + \frac{\alpha\beta}{2})$.
$EC_1(r_1 + \frac{\epsilon}{2}, 0, 0) = r_1 + \frac{\epsilon}{2} + x_1(1,0)\frac{\alpha\beta}{4} + y_1(1,0,1)(r_2 + \frac{\epsilon}{2} + \frac{\delta}{2} + \frac{\alpha\beta}{2})$.
$x_1(1,0) = 0$ by the condition $[(\exists i \in \{1,2\})(p_i = 0) \rightarrow (\forall j \in \{1,2\})(p_j = 1 \rightarrow x_j = 0)]$; and $y_1(1,0,1) = 0$ as $N^0 = \{1,2\}$ is the smallest or one of the smallest among N' such that $\{i \in \{1,2,3\} \mid p_i = 0\} = N' \neq \emptyset \wedge \sum_{i \in N'} y_i \neq 1$.
Therefore:
$EC_1(r_1 + \frac{\epsilon}{2}, 0, 0) - EC_1(0,0,0) = r_1 + \frac{\epsilon}{2} - x_1(0,0)\frac{\alpha\beta}{2} - y_1(0,0,1)(r_1 + r_2 + \epsilon + \delta + \frac{\alpha\beta}{2})$
$= r_1 + \frac{\epsilon}{2} - x_1(0,0)\frac{\alpha\beta}{2} - y_1^0(t + \frac{\alpha\beta}{2})$
$\geq r_1 + \frac{\epsilon}{2} - \alpha\beta - y_1^0 t$
$> r_1 + \frac{\epsilon}{2} - \alpha - y_1^0 t$
> 0, as $r_1 + \frac{\epsilon}{2} - y_1^0 t > \alpha$. (P4.1)

$EC_2(0,0,0) = x_2(0,0)\frac{\alpha\beta}{2} + y_2(0,0,1)(r_1 + r_2 + \epsilon + \delta + \frac{\alpha\beta}{2})$.
$EC_2(0, r_2 + \frac{\epsilon}{2}, 0) = r_2 + \frac{\epsilon}{2} + x_2(0,1)\frac{\alpha\beta}{4} + y_2(0,1,1)(r_1 + \frac{\epsilon}{2} + \frac{\delta}{2} + \frac{\alpha\beta}{2})$.
$x_2(0,1) = 0$ by the condition $[(\exists i \in \{1,2\})(p_i = 0) \rightarrow (\forall j \in \{1,2\})(p_j = 1 \rightarrow x_j = 0)]$; and $y_2(0,1,1) = 0$ as $N^0 = \{1,2\}$ is the smallest or one of the smallest among N' such that $\{i \in \{1,2,3\} \mid p_i = 0\} = N' \neq \emptyset \wedge \sum_{i \in N'} y_i \neq 1$.
Therefore:
$EC_2(0, r_2 + \frac{\epsilon}{2}, 0) - EC_2(0,0,0) = r_2 + \frac{\epsilon}{2} - x_2(0,0)\frac{\alpha\beta}{2} - y_2(0,0,1)(r_1 + r_2 + \epsilon + \delta + \frac{\alpha\beta}{2})$
$= r_2 + \frac{\epsilon}{2} - x_2(0,0)\frac{\alpha\beta}{2} - y_2^0(t + \frac{\alpha\beta}{2})$
$\geq r_2 + \frac{\epsilon}{2} - \alpha\beta - y_2^0 t$
$> r_2 + \frac{\epsilon}{2} - \alpha - y_2^0 t$
> 0, as $r_2 + \frac{\epsilon}{2} - y_2^0 t > \alpha$. (P4.2)

$EC_3(0,0,0) = y_3(0,0,1)(r_1 + r_2 + \epsilon + \delta + \frac{\alpha\beta}{2})$.
$EC_3(0,0,\alpha) = \alpha + y_3(0,0,1)(r_1 + r_2 + \epsilon + \delta)$.
Therefore:
$EC_3(0,0,\alpha) - EC_3(0,0,0) = \alpha - y_3(0,0,1)\frac{\alpha\beta}{2}$
$\geq \alpha - \frac{\alpha\beta}{2}$
> 0. (P4.3)
From (P4.1)-(P4.3), it follows that $(0,0,0) \notin M$ is a Nash equilibrium. Therefore f is inefficient for the application belonging to $\mathcal{A}$ considered herein.

Case: $N^0 = \{2,3\}$

Designate $y_2(1,0,0)$ by y_2^0 and $y_3(1,0,0)$ by y_3^0. By assumption, $y_2^0 + y_3^0 < 1$.
Let $t > 0$.

If $y_i^0 > 0, i = 2, 3$, then choose r_i such that: $0 < y_i^0 t < r_i < \frac{y_i^0}{y_2^0 + y_3^0} t$.
If $y_i^0 = 0, i = 2, 3$, then choose $r_i = 0$.
Thus we have: $0 \leq r_2 + r_3 < t$.
Choose v such that: $r_2 + r_3 < v < t$.
Let: $\delta = t - v$; $\epsilon = v - (r_2 + r_3)$; and $0 < \beta < 1$.
Let: $0 < \alpha < min\{r_2 + \frac{\epsilon}{2} - ty_2^0, r_3 + \frac{\epsilon}{2} - ty_3^0\}$.

Consider the application given by:
$C_1 = \{0, \alpha\}; C_2 = \{0, r_2 + \frac{\epsilon}{2}\}; C_3 = \{0, r_3 + \frac{\epsilon}{2}\}$.
Let L_1 be as given in the following array:

$L_1(c_1, c_2)$

	$c_2 = 0$	$c_2 = r_2 + \frac{\epsilon}{2}$
$c_1 = 0$	$\frac{\alpha\beta}{2}$	$\frac{\alpha\beta}{4}$
$c_1 = \alpha$	$\frac{\alpha\beta}{4}$	0

Let L_2 be specified as given in the following two arrays:

$L_2(0, c_2, c_3)$

	$c_3 = 0$	$c_3 = r_3 + \frac{\epsilon}{2}$
$c_2 = 0$	$r_2 + r_3 + \epsilon + \delta + \frac{\alpha\beta}{2}$	$r_2 + \frac{\epsilon}{2} + \frac{\delta}{2} + \frac{\alpha\beta}{2}$
$c_2 = r_2 + \frac{\epsilon}{2}$	$r_3 + \frac{\epsilon}{2} + \frac{\delta}{2} + \frac{\alpha\beta}{2}$	$\frac{\alpha\beta}{2}$

$L_2(\alpha, c_2, c_3)$

	$c_3 = 0$	$c_3 = r_3 + \frac{\epsilon}{2}$
$c_2 = 0$	$r_2 + r_3 + \epsilon + \delta$	$r_2 + \frac{\epsilon}{2} + \frac{\delta}{2}$
$c_2 = r_2 + \frac{\epsilon}{2}$	$r_3 + \frac{\epsilon}{2} + \frac{\delta}{2}$	0

As we have $(\forall (c_1, c_2, c_3), (c_1', c_2', c_3'))[[c_1 = 0 \wedge c_1' = \alpha \wedge c_2 = c_2' \wedge c_3 = c_3' \rightarrow L_1(c_1, c_2) - L_1(c_1', c_2') = \frac{\alpha\beta}{4} \wedge L_2(c_1, c_2, c_3) - L_2(c_1', c_2', c_3') = \frac{\alpha\beta}{2}] \wedge [c_1 = c_1' \wedge c_2 = 0 \wedge c_2' = r_2 + \frac{\epsilon}{2} \wedge c_3 = c_3' \rightarrow L_1(c_1, c_2) - L_1(c_1', c_2') = \frac{\alpha\beta}{4} \wedge L_2(c_1, c_2, c_3) - L_2(c_1', c_2', c_3') = r_2 + \frac{\epsilon}{2} + \frac{\delta}{2}] \wedge [c_1 = c_1' \wedge c_2 = c_2' \wedge c_3 = 0 \wedge c_3' = r_3 + \frac{\epsilon}{2} \rightarrow L_2(c_1, c_2, c_3) - L_2(c_1', c_2', c_3') = r_3 + \frac{\epsilon}{2} + \frac{\delta}{2}]]$, it follows that TSC is uniquely minimized at $(0, r_2 + \frac{\epsilon}{2}, r_3 + \frac{\epsilon}{2})$.

We have:
$EC_1(0, 0, 0) = x_1(1, 0)\frac{\alpha\beta}{2} + y_1(1, 0, 0)(r_1 + r_2 + \epsilon + \delta + \frac{\alpha\beta}{2})$.
$EC_1(\alpha, 0, 0) = \alpha + x_1(1, 0)\frac{\alpha\beta}{4} + y_1(1, 0, 0)t$.

$x_1(1,0) = 0$ by the condition $[(\exists i \in \{1,2\})(p_i = 0) \rightarrow (\forall j \in \{1,2\})(p_j = 1 \rightarrow x_j = 0)]$.
Therefore:

$$EC_1(\alpha, 0, 0) - EC_1(0,0,0) = \alpha + y_1(1,0,0)t - y_1(1,0,0)(t + \tfrac{\alpha\beta}{2})$$
$$= \alpha - y_1(1,0,0)\tfrac{\alpha\beta}{2}$$
$$\geq \alpha - \tfrac{\alpha\beta}{2}$$
$$> 0. \qquad \text{(P4.4)}$$

$EC_2(0,0,0) = x_2(1,0)\frac{\alpha\beta}{2} + y_2(1,0,0)(t + \frac{\alpha\beta}{2})$.
$EC_2(0, r_2 + \frac{\epsilon}{2}, 0) = r_2 + \frac{\epsilon}{2} + x_2(1,1)\frac{\alpha\beta}{4} + y_1(1,1,0)(r_3 + \frac{\epsilon}{2} + \frac{\delta}{2} + \frac{\alpha\beta}{2})$.
$x_2(1,0) = 1$ by the condition $[(\exists i \in \{1,2\})(p_i = 0) \rightarrow (\forall j \in \{1,2\})(p_j = 1 \rightarrow x_j = 0)]$; and $y_1(1,1,0) = 0$ as $N^0 = \{2,3\}$ is the smallest or one of the smallest among N' such that $\{i \in \{1,2,3\} \mid p_i = 0\} = N' \neq \emptyset \wedge \sum_{i \in N'} y_i \neq 1$.
Therefore:

$$EC_2(0, r_2 + \tfrac{\epsilon}{2}, 0) - EC_2(0,0,0) = r_2 + \tfrac{\epsilon}{2} + x_2(1,1)\tfrac{\alpha\beta}{4} - \tfrac{\alpha\beta}{2} - y_2(1,0,0)(t + \tfrac{\alpha\beta}{2})$$
$$= (r_2 + \tfrac{\epsilon}{2} - y_2^0 t) + x_2(1,1)\tfrac{\alpha\beta}{4} - \tfrac{\alpha\beta}{2} - y_2^0\tfrac{\alpha\beta}{2}$$
$$\geq (r_2 + \tfrac{\epsilon}{2} - y_2^0 t) - \alpha\beta$$
$$> (r_2 + \tfrac{\epsilon}{2} - y_2^0 t) - \alpha$$
$$> 0. \qquad \text{(P4.5).}$$

$EC_3(0,0,0) = y_3(1,0,0)(r_2 + r_3 + \epsilon + \delta + \frac{\alpha\beta}{2})$.
$EC_3(0,0,r_3 + \frac{\epsilon}{2}) = r_3 + \frac{\epsilon}{2} + y_3(1,0,1)(r_2 + \frac{\epsilon}{2} + \frac{\delta}{2} + \frac{\alpha\beta}{2})$.
We obtain $y_3(1,0,1) = 0$ as $N^0 = \{2,3\}$ is the smallest or one of the smallest among N' such that $\{i \in \{1,2,3\} \mid p_i = 0\} = N' \neq \emptyset \wedge \sum_{i \in N'} y_i \neq 1$.
Therefore:

$$EC_3(0,0,r_3 + \tfrac{\epsilon}{2}) - EC_3(0,0,0) = r_3 + \tfrac{\epsilon}{2} - y_3(1,0,0)(t + \tfrac{\alpha\beta}{2})$$
$$= (r_3 + \tfrac{\epsilon}{2} - y_3^0 t) - y_3^0\tfrac{\alpha\beta}{2}$$
$$> (r_3 + \tfrac{\epsilon}{2} - y_3^0 t) - \alpha$$
$$> 0. \qquad \text{(P4.6)}$$

From (P4.4)-(P4.6), it follows that $(0,0,0) \notin M$ is a Nash equilibrium. Therefore f is inefficient for the application belonging to $\mathcal{A}$ considered herein.

Thus in each case of violation of the condition $[(\exists i \in \{1,2,3\})(p_i = 0) \rightarrow (\forall j \in \{1,2,3\})(p_j = 1 \rightarrow y_j = 0)]$, it has been shown that f is inefficient for some application belonging to $\mathcal{A}$. The proposition, therefore, stands proved.

□

Theorem 2 *A simple liability rule for successive joint torts $f : \{0,1\}^3 \mapsto [0,1]^5$ is efficient for for every application $< C_1, C_2, C_3, L_1, L_2, (c_1^*, c_2^*, c_3^*) \in M >$ belonging to $\mathcal{A}$ iff it satisfies the condition of negligence liability for successive joint torts (NL-SJT).*

Proof: Let $f : \{0,1\}^3 \mapsto [0,1]^5$ be a simple liability rule for successive joint torts. If f satisfies NL-SJT then f is efficient for all applications $< C_1, C_2, C_3, L_1, L_2, (c_1^*, c_2^*, c_3^*) \in M >$ belonging to $\mathcal{A}$ by Corollary 1; and if f is efficient for all applications $< C_1, C_2, C_3, L_1, L_2, (c_1^*, c_2^*, c_3^*) \in M >$ belonging to $\mathcal{A}$ then it satisfies NL-SJT by Propositions 3 and 4.

□

4 Concluding Remarks

In this paper it has been shown that NL-SJT is a sufficient condition for a liability rule for successive joint torts to be efficient with respect to $\mathcal{A}$; also that NL-SJT is a necessary condition for a simple liability rule for successive joint torts to be efficient with respect to $\mathcal{A}$. An obvious question that arises is as to whether NL-SJT is a characterizing condition for efficiency with respect to $\mathcal{A}$ also for the class of all liability rules for successive joint torts, and not merely for the subclass of all simple liability rules for successive joint torts. Because of the generality of the notion of a liability rule for successive joint torts, the necessity question poses seemingly intractable difficulties.

In view of the facts (a) that a necessary condition for any simple liability rule for successive joint torts to be efficient with respect to $\mathcal{A}$ is that it satisfy the condition of NL-SJT, (b) that NL-SJT is a sufficient condition for any liability rule for successive joint torts to be efficient with respect to $\mathcal{A}$, and (c) that the class of simple liability rules for successive joint torts is a proper subclass of the class of liability rules for successive joint torts; it follows that logically there are only two possibilities regarding efficiency conditions for the entire class of liability rules for successive joint torts. These possibilities are: (i) NL-SJT is a necessary and sufficient condition for any liability rule for successive joint torts to be efficient with respect to $\mathcal{A}$. (ii) There is no condition which is both necessary and sufficient for any liability rule for successive joint torts to be efficient with respect to $\mathcal{A}$. It is an open question as to which of these two possibilities in fact holds.

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